INTRODUCTION

Freshwater resources and problems facing its management

Freshwater is a finite and vulnerable resource, essential to sustain life, development and the environment (UNEP 2003). The need for adequate freshwater supplies for human survival is obvious. It fundamentally fuels economic development. Regions with limited water supplies exhibit low economic activity levels. Sustainable use of water resources should contribute directly to sustainable economic development and to maintaining the health of the environment that supports this development (UNEP 2003). As a critical water resource for the local people, the quantity and quality of the water of each lake can either provide great benefits to them or threaten their lives (Ballator & Muhandiki 2001).

Lakes consist of two distinct, yet interrelated components, the drainage basin and the water body itself. The vast majority of readily accessible water resources are contained in numerous small sized lakes of a depth usually less than 20 meters. These lakes are the most accessible to the greater number of people and are important to communities in that they provide water, food as well as other resources crucial to their livelihood.

The provision of access to clean and safe water is one of the major challenges of sustainable development. However, by 2025, the majority of the world's population will live in water stressed areas. Thirty-three megacities with populations above 8 million people and 500 cities with populations above 1 million people are estimated to be there by 2025. The world's population is growing at a rate of 100 million per year.

Eutrophication is a chronic environmental problem that will not abate because there is no zero discharge option for humans, and organic and nutrient-rich wastes will continue to be added to lakes, rivers and reservoirs (UNEP 2002).

Humans have, throughout the world, constructed artificial lakes, also called reservoirs in different regions of the world, primarily for addressing the problems of water scarcity. Nearly all of the worlds' river systems have reservoirs in their drainage basins. 800,000 reservoirs are estimated to be in operation worldwide and approximately 1,700 large reservoirs, particularly in developing countries, are currently under construction. (UNEP 2003).

Lakes are among the most vulnerable and fragile aquatic ecosystems. They are sinks for inflowing substances, such as sediments, minerals, aquatic plant nutrients and organic materials from their drainage basins. This material tends to accumulate in the water column or at the bottom of the lake. Human activities in typically densely populated or industrialized drainage basins have significantly accelerated the natural ageing process of drainage basins and degrade water quality and the lake bottom environment. Because of this, lakes serve as sensitive indicators and unique records of the effect of human and natural activities inside their drainage basins and sometimes from activities occurring outside their basins.

Lakes around the world are beset with problems affecting their sustainable use. The use of water and land resources within a drainage basin determines the types and magnitudes of its environmental stresses. Although eutrophication is a natural process in the aging of lakes and some estuaries, human activities have greatly accelerated eutrophication by increasing the rate at which nutrients and organic substances enter aquatic ecosystems from their surrounding watersheds. Agricultural and urban runoff, leaking septic systems, sewage discharges, and eroded stream banks can increase the flow of nutrients and organic substances into aquatic systems. These substances have been found to stimulate the growth of algae, creating conditions that interfere with the recreational use of lakes and estuaries together with the health and diversity of indigenous fish, plant, and animal populations (http://www.epa.gov/maia/html/eutroph.html). Furthermore, because most lakes are impacted simultaneously by multiple problems, their remediation is more difficult and costly than addressing one problem alone. Management of water bodies is fairly simple when it serves few purposes and water is abundant. The task becomes difficult when the water body serves multiple purposes in a water stressed environment.

Urban water management (UWM) involves the qualitative (hygienic) and quantitative aspects of all water in urban settings (Siebel and Gijzen 2002). Lake Chivero in Harare,

Zimbabwe is a typical example of a water resource that has succumbed to unsustainable water uses and environmental practices in its drainage basin:

Background Information on Lake Chivero

Lake Chivero, formerly Lake McIlwaine, is located at 30°46'E to 30°52'E and 17°52'S to 17°56'S, in tropical savannah of Southern Africa (Magadza 2004). It is a tropical impoundment of the Manyame River at Hunyani Poort built in 1952 to supply the City of Harare with water for both domestic and industrial use (Bailey *et al.*). Water sport, fisheries and tourism later on flourished (Magadza 2003). The lake has a capacity of 247 million cubic meters and a length of 10 kilometers with an earthen dam wall, 40 meters high and 200 meters long. The lake has a mean depth of 9.5m and a maximum depth of 27m (Marshall and Falconer 1973). The Upper Manyame catchment area is 2136km^2 (Thorton & Nduku 1982) and the lake receives water from 3 major tributaries of the upper Manyame River, namely, The Manyame, Mukuvisi and Marimba Rivers. The Manyame and the Mukuvisi Rivers flow through the City of Harare and as a result, Harare is in the catchment of its water supply.

The Manyame River flows past the City of Chitungwiza and thus the lake also receives effluent from this urban centre (Bailey *et al.*1996). The river flows through commercial farm land and Seke communal lands before reaching Harava and Seke Dams.

The Mukuvisi River flows through the industrial area of Masasa and past Mukuvisi Woodlands Conservancy Park. It then flows through the south side of Harare City Centre, past Arcadia landfill sites and Graniteside industrial area. The river then flows past the Firle sewage treatment works which are situated on the Mukuvisi River downstream of the urban centre.

The Marimba River rises in the University of Zimbabwe campus, flows through the North-west part of Harare's commercial centre and then flows through the industrial area of Workington. Crowbrough sewage treatment works is situated in the western outskirts of Harare. After the sewage works, the Marimba River flows through a commercial farming area (Bailey *et al*. 1996).

The lake is within a recreational park managed by the Department of National Parks and Wildlife Management. Activities such as angling, commercial fishing, sailing and boating are some of the activities that are undertaken. Lake Chivero Recreational

Park also provides an environment for a number of large mammals namely: Kudu, white rhino, zebra, sable, impala, wildebeest, eland, tsessebe, warthog, waterbuck, giraffe and over 300 species of birds in the adjacent game park (UNEP 2002). The game park is on the south bank of the lake and encompasses 14km of the lake's stretch (Munzwa 1982). The shoreline along the lake has a length of 60km and marginal vegetation comprising the miombo woodland vegetation and typical riverine reeds namely: *Phragmites* sp., *Typha latifolia* and *Cyperus* sp. along the north and south banks (Ndebele 2003).

The invasive weed, *Eichhornia crassipes* (water hyacinth), and *Hydrocotly* are the most common floating weeds in the lake. Other aquatic macrophytes such as the *Azolla* sp. and the water lily (*Nymphea* sp.) are also found in the lake. The National Parks Authority (formerly, the Department of National Parks and Wildlife Management) governs the activities of the lake whilst the Harare City Council's Department of Works and the municipality are responsible for the treatment of water and waste discharges. The Zimbabwe National Water Authority is responsible for pollution control. The legislative instrument controlling the use of water in Zimbabwe is the water Resources Act of 1998 which is administered by the Zimbabwe National Water Authority (ZINWA).

Lake Chivero has been intensively studied over the years (Marshall & Falconer 1973; Nduku 1976; Thornton 1982; Magadza 1994, 1997; 2003; Machena 1997; Moyo 1997) and is ranked among the most researched African reservoirs. All the studies on this lake have a common concern of deteriorating water quality (Magadza 2003).

History of the State of the Lake.

In the 1960's, the first indication of the eutrophic state of the Lake was the appearance of a major blue-green algal bloom (Marshall 1996). This became a permanent feature by 1964 making water purification very difficult. Gastro-enteritis that occurred in children was thought to be caused by these algal blooms (Zilberg 1996). Massive fish kills were recorded in 1970 on the lake and a year later, the lake was described as hypereutrophic, with massive algal and macrophytic infestations and extensive deoxygenation, particularly at times of overturn (Thorton & Nduku 1982). The lake returned to a mesotrophic state after the City of Harare installed a BNR sewage treatment plant and diverted partially treated sewage to irrigate pasture lands. This resulted in a 94% reduction in phosphate levels in the lake (Thorton 1980). During the droughts of the 1982-1984 periods, outbreaks of water hyacinth occurred and the pattern of infestations has continued to the present. Over the years the lake has failed to spill due to reduced inflows as a result of reduced rainfall in the lakes catchment. From 1990 to 1996, the lake failed to spill (Bailey *et al.*1996, Magadza 2003). There were fish deaths recorded in 1991 and other cases were recorded in 1996, where the biggest mass death of fish occurred (Moyo 1996). Currently, there is the problem of water hyacinth infestations in the lake. This has been a result of the ecological imbalance that has been caused by eutrophication. Water samples that have recently been taken from the lake show that the lake is hypereutrophic.

Phosphorous and nitrogen are the most important limiting nutrients on productivity in Zimbabwean impoundments such as Lake Chivero (Thorton & Nduku 1982). The levels of phosphorous and nitrogen have exponentially risen as evidenced by results of water sampled in the 1993-1995 period. Compared to the 1970's average values of 0.45mg/l of nitrates and 0.2mg/l of phosphates, the 1993-1995 values exceeded this by recording 7mg/l of phosphates and 10mg/l of nitrates (Thorton & Nduku 1982). In the 1970's, the lake was then considered to be hypereutrophic with the above measurement and therefore compared to the current measurements, the lake is in an even more critical condition.

Monitoring of levels of heavy metals in the waters and fish of Lake Chivero revealed that copper, cadmium and nickel were in dangerously high concentrations (Gumbo 1997). In contrast, the levels of heavy metals were in low concentrations in 1974 (Greichus *et al.* 1978).

Legislative and Institutional Framework Governing Water Pollution

Several agencies have the responsibility of water pollution control in Zimbabwe. The Ministries of Lands and Agriculture, Water Resources, Local Government, Environment and Tourism, and Health and Child Welfare have the authority divided amongst them. Four major government agencies are directly involved in pollution control at national level and two are particularly concerned with planning and financial management aspects (JICA 1996). The management is dissected as follows:

1. The Department of National Parks and Wildlife Management administers the lake water and its environs because the lake is a national recreational facility.
2. Pollution control is invested in the Ministry of Health.

3. Zimbabwe's Noxious Weed Act, which controls the management of exotic and nuisance weeds, is administered by the Department of Agriculture, on behalf of the Ministry of Natural Resources, Mining and Tourism. The act lays the responsibility of eradicating noxious weeds on the property holder or occupier, in this case the Department of Parks and Wildlife Management.

4. The dam wall and related works were constructed by the State for the City of Harare and ownership of the facility remains with the State.

5. The waterworks and sewage disposal facilities are owned by the Harare Municipality (Magadza 2003).

The 1998 Zimbabwe Water Act calls for the formation of catchment authorities, responsible for catchment development, water allocation and pricing, and water quality under supervision of the Zimbabwe National Water Authority. Prior to this act, no such institutional catchment management facility existed (Magadza 2003). The Water Act focuses on the development and use of water resources. It has a short term basis on use "here and now" and as a result it does not reflect provisions for environmental issues such as pollution. The legislation in place is more of reactive than preventative and the process of prosecution is very slow. Zimbabwe's environmental legislation is contained in 18 different statutes and is administered by at least 8 different Ministries and the Ministry of Environment and Tourism is very vague when it comes to the issue of water quality and has trifling powers under the Natural Resources Act and Parks and Wildlife Act. Gumbo (1997) points out that a "liassez faire" attitude prevails which emanates from a fragmented legislation and uncoordinated sectorial approach. In this situation, confusion prevails and nobody takes responsibility.

POLLUTION CONTRIBUTIONS OF MAJOR RIVERS INTO LAKE CHIVERO

The three rivers in the upper Manyame catchment have their contributions to Lake Chivero's nutrient loads, which are determined by the areas in which the rivers pass through:

The Mukuvisi River

Pollution in the Mukuvisi River has been identified to be from the following sources: Industrial discharges from the Masasa, Graniteside and the Southerton industrial areas, leachate from the land filled areas along the river banks and the contribution of the Firle sewage works (Zaranyika 1996). Almost all of the rivers catchment is covered by the City of Harare. In the upper reach of the river, wastes from a phosphate fertilizer manufacturing company (ZIMPHOS) and other manufacturing industries in the Masasa area release their effluent into the river. The residential areas of Hillside and Braeside, the railway yard and the main commercial areas of the City centre have their share of contributions into the river. The river then passes through a number of landfill sites which produce leachate. The river then passes through the residential areas of Mbare, Parktown, Waterfalls, Highfields and Glen Norah which are densely populated suburbs. The industrial area of Southerton releases its sewage effluent into the river. Firle sewage works further downstream disposes its treated sewage effluent into the Mukuvisi River

(Zaranyika 1996). The Mukuvisi River was found to be a major source of pollution of Lake Chivero.

The Marimba River

The Crowbrough sewage treatment plant near Mufakose treats both domestic and industrial waste water. A number of industries, electroplating and food processing companies (Mathuthu *et al.* 1996), are located along or near the river into which they discharge their effluent. The waste water is enriched in trace heavy metals, oils, detergents and other inorganic compounds. Inorganic plant nutrients in the form of phosphates, potassium and nitrates also constitute the sewage water. The Marimba River contributes 12% of hydraulic load but over 25% of the total nitrogen load and approximately 35% of the total phosphorous load into Lake Chivero (Nhapi *et. al* 2001).

1.5.3 The Manyame River

The Manyame River flows past the City of Chitungwiza. Activities in the town have been noted to contribute to the enrichment of the river. The chief culprit was identified to be that of the sewage treatment works that was observed to release raw or partially treated sewage into the Manyame River. Its sewerage system has been noted to be insufficient. Marshall (1994) pointed out that the increased algal blooms in Lake Chivero was partially a result of sewage effluent discharges from Chitungwiza as well as a poorly treated sewage being fed into the Nyatsime River, a tributary of the Manyame River.

Pollution in the lakes tributaries affects the lake in that it has resulted in the lowering of the rivers’ self purification capacity as it affects the biological processes that occur in it. Within the main tributaries, the Mukuvisi is the highest contributor of nutrients to the lake followed by the Marimba River and the lowest contributor being the Manyame River (Thorton 1980, Marshall & Falconer 1973). The sources of pollution are both point source (industrial, municipal and sewage wastes) as well as non-point sources such as organic pollution by agricultural chemicals, storm water run-off, land degradation, solid wastes, livestock, wildlife and poultry farming (Moyo and Mtetwa 2002).

PROBLEMS IN LAKE CHIVERO

Eutrophication in Lake Chivero

Eutrophication is one of the most widespread environmental problems encountered in inland waters (UNEP 2003). Symptoms of eutrophication include algal scums and toxins derived from algal blooms, massive infestations of certain aquatic plants, increased incidence of water-related diseases, turbid water, noxious odors and poor tasting water, low levels of dissolved oxygen, and incidents of fish kills. Eutrophication results from processes associated with plant nutrients particularly phosphorous and nitrogen. Lake Chivero is highly eutrophic because of several factors that are at play in its catchment. The most obvious symptom of eutrophication of the lake was the appearance of blue-green algal blooms, principally M*icrocystis aeruginosa, Anabaena* sp. (Marshall 1996) and *Anabaenopsis* sp. (Magadza pers. comm.). Over the years the density of algae has increased in the lake and this is a reflection of changing water quality (Personal assessment).

Immediate causes of eutrophication

Due to various human activities in the Upper Manyame catchment, waste substances have found their way into the water system and eventually into Lake Chivero. The following are the immediate causes of eutrophication in Lake Chivero:

Population pressure in the catchment

As the City of Harare continues to grow the demand for water has increased dramatically. Chitungwiza, Ruwa and Epworth are also increasing in population. This has impacted severely on the lakes water quality. The catchment of Lake Chivero consists of approximately 10% urban and 90% rural development (Magadza 1996). Upstream of the urban areas, the catchment comprises both commercial and communal farmlands. In the latter, the land is deforested, overgrazed and scarred with erosion. Natural stream beds have been replaced by gullies (Moyo 1996).

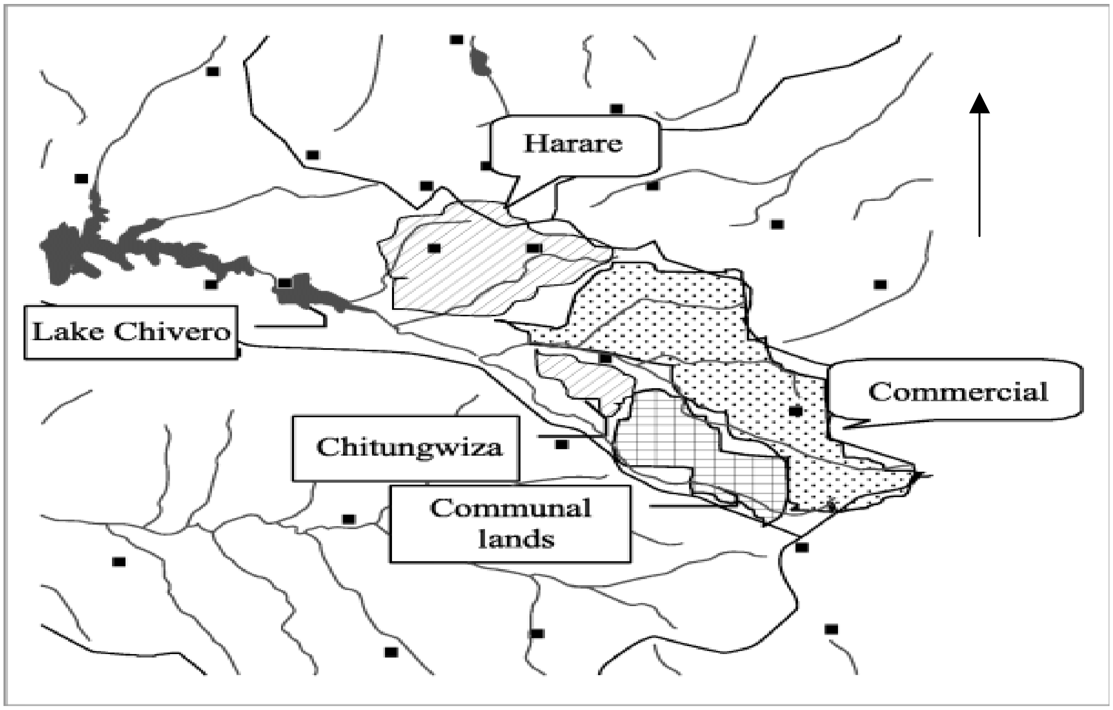
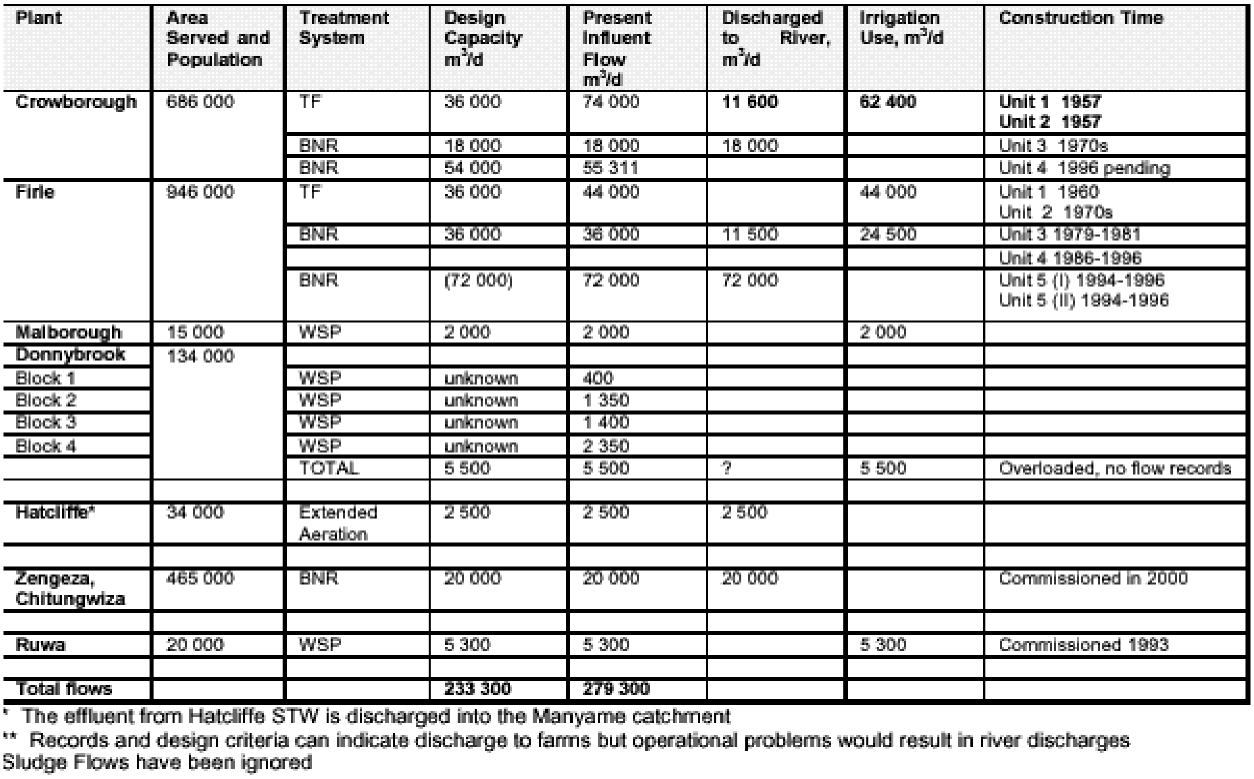


Fig 1: Map of Lake Chivero Catchment (Magadza 2003)

The three major rivers in the Upper Manyame catchment release large quantities of waste material that has been identified to be the main reason why Lake Chivero is in such a eutrophic state. The major sources of pollution in Lake Chivero have been identified as being urban run-off, sediments and industrial effluents (Munzwa 1982). The Manyame catchment area is the most urbanized in Zimbabwe and the increase in population has come with severe problems (Zanamwe 1996). The Cities of Harare, Chitungwiza and the towns of Chinhoyi, Norton and Ruwa are in the catchment. The Upper Manyame catchment has a population of 1 903 510 (www.zimrelief.info) which is approximately 16% of the national population. Due to the historical back ground of the high density areas, which were planned to be settlements for a small group of people working in the city, in the colonial times of the then Rhodesia, most were built with poor services and amenities. Chitungwiza, for example, has a population of 321 782, which is contained on the smallest pieces of land for its size in Zimbabwe. Development in Chitungwiza has clearly outstripped urban infrastructure. Its sewerage system is insufficient to deal with sewage flowing into it, with the result that raw sewage outflows onto the streets, and eventually ends up in rivers untreated as surface runoff (Gumbo 1997). Frequent problems of sewage breakdowns are experienced in high density suburbs. When the first major algal blooms were observed in Lake Chivero in 1960, 30 000m^3 of sewage effluent was released per day from Chitungwiza. Marshall (1994) attributed the increase in algal blooms in recent studies to the increased sewage output with the City of Chitungwiza contributing up to 160 000m^3 per day. The reason cited for such tardy actions is that of gross under-funding (Gumbo 1997). Population influxes into the Manyame catchment have adversely affected the ecology of the catchment. This has led the expansion of areas to accommodate the new inhabitants, thus implying the clearing of vegetation and destruction of riverine systems as well as wetlands. The developments in the catchment have therefore led to the straining of infrastructure. The total capacity of sewage works in the Manyame catchment is estimated to be 233 300m^3/d but the plants are receiving an excess of 279 300 m^3/d (Nhapi 2001), a clear indication of overloading.

Table 1: Existing Sewage Treatment Works in the greater Harare Area (Source: JICA, 1996)



Plant	**Area Served and Population**	**Treatment System**	**Design Capacity m^3/d**	**Present Influent Flow m^3/d**	**Discharged to River, m^3/d**	**Irrigation Use, m^3/d**	**Construction Time**
Crowborough	686 000	TF	36 000	74 000	**11 600**	**62 400**	**Unit 1 1957** **Unit 2 1957**
		BNR	18 000	18 000	18 000		Unit 3 1970s
		BNR	54 000	55 311			Unit 4 1996 pending
Firle	946 000	TF	36 000	44 000		44 000	Unit 1 1960 Unit 2 1970s
		BNR	36 000	36 000	11 500	24 500	Unit 3 1979-1981
							Unit 4 1986-1996
		BNR	(72 000)	72 000	72 000		Unit 5 (I) 1994-1996 Unit 5 (II) 1994-1996
Malborough	15 000	WSP	2 000	2 000		2 000	
Donnybrook	134 000						
Block 1		WSP	unknown	400			
Block 2		WSP	unknown	1 350			
Block 3		WSP	unknown	1 400			
Block 4		WSP	unknown	2 350			
		TOTAL	5 500	5 500	?	5 500	Overloaded, no flow records
Hatcliffe*	34 000	Extended Aeration	2 500	2 500	2 500		
Zengeza, Chitungwiza	465 000	BNR	20 000	20 000	20 000		Commissioned in 2000
Ruwa	20 000	WSP	5 300	5 300		5 300	Commissioned 1993
Total flows			**233 300**	**279 300**			

* The effluent from Hatcliffe STW is discharged into the Manyame catchment

** Records and design criteria can indicate discharge to farms but operational problems would result in river discharges

Sludge Flows have been ignored

Coupled with industrial development as well as an increase in commercial land, residential expansion has contributed to the eutrophication problem in Lake Chivero. The influx of people into the city in pursuit of employment, when industries were established and expanded and the failure to match the infrastructure to the increasing demand, are the reasons why the infrastructure has failed to cater for the needs of the population. It was thus pointed out by Marshall (1994) that pollution problems tend to increase with industrialization. The problem of Chitungwiza and Norton can be attributed to the fact that they have no industrial base to generate income for their infrastructure (Magadza pers. comm.). Gumbo (1997) noted that the quantity of pollution loads increase yearly at a higher rate than the expansion of treatment facilities required and the type of pollution loads have become diversified due to the variety of industrial developments.

Table 2: Population trends in Harare from 1992-2002 (Source: www.zimrelief.info)

District	1992	2002
Harare Rural	20 606	23 310
Harare Urban	1 184 169	1 444 534
Chitungwiza	274 035	321 782
Epworth	N/A	113 884

Other sources of pollution

Storm water drainage in the catchment flows into rivers without undergoing any treatment process. An increase in urbanization has led to an increase in the number of buildings and pavements which lead to an increase in surface runoff which is channeled into the storm water drainage system. Since these drain directly into the rivers, there is no opportunity for environmental assimilation. Nduku and Thorton (1982) from their estimations found that the diffuse storm water runoff can potentially supply sufficient nutrients to lakes such as Lake Chivero to maintain a eutrophic state. The diagram below summarises the above:

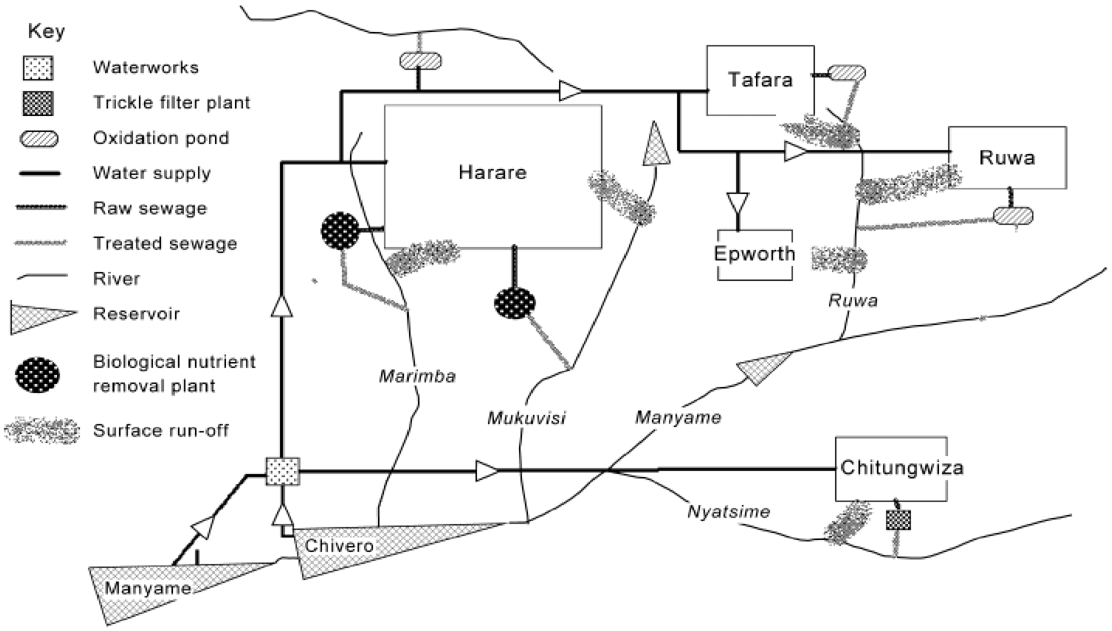


Fig 2: Schematic presentation of settlements, waste management and water supply in Greater Harare and Chitungwiza (Source: Magadza 2003)

Using Modelling as a management tool

Models have become widely used tools in lake management. Due to increased urbanisation and the rapid development in technology, there have been wide varieties of pollutants and nutrients being diffused into natural environments. High nutrient and pollutant loads alter the food web hierarchy of many lakes by causing rapid growth of algae and bacteria, thus resulting in deterioration of water quality and ecosystem functioning. Models became a tool to predict the potential effects on the environment of discharging these pollutants and nutrients. Several models with a wide range of complexity have been developed due to variability between ecosystems and the available data. With sound data on hydrology, ecology and the socio-economic situation around the lakes, it is possible to extract the features of the lakes that are under consideration. This enables preparation of sustainable management plans with the help of different simulations.

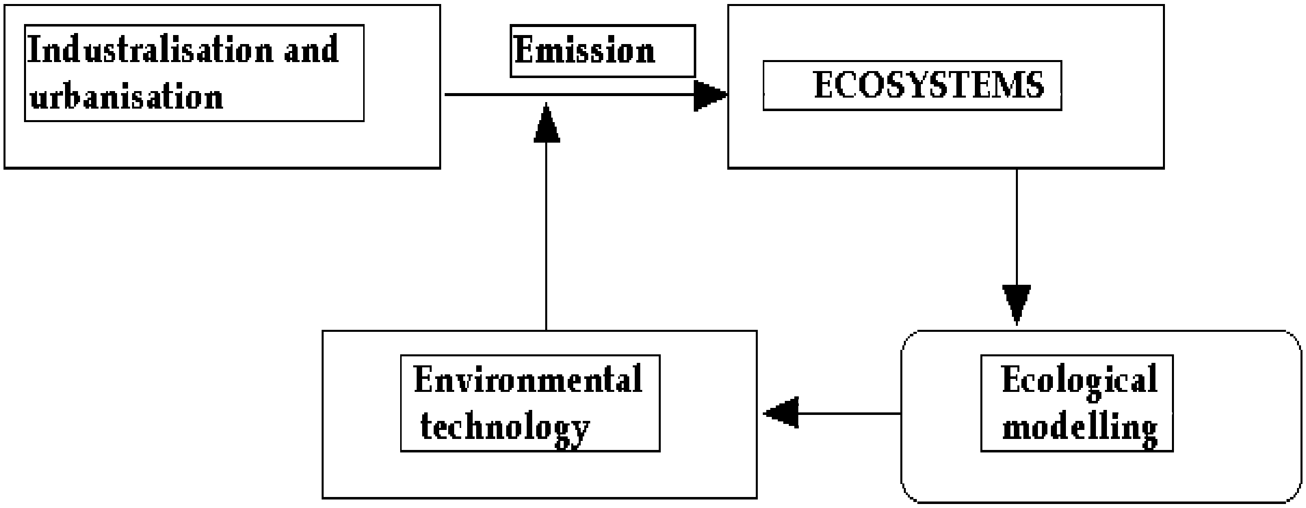


Figure 3: The role of ecological modelling in lake resource management

Ecological models have been used increasingly in ecological management as an instrument to understand the properties of the ecosystems. Although, the use of models in the ecological context is relatively new and there are just a few guides are available for the construction of ecological management models. First step of the constructing an ecological model is defining the problem and its parameters in space and time. Because all ecosystems have distinctive characters, a comprehensive knowledge of the system that is going to be modeled is often needed.

According to Jørgensen, an ecological model consists of five elements:

1- Forcing functions or external variables, which are the variables of an external nature that influence the state of the ecosystem.

2- State variables, indicates the state of the ecosystems. A model, depending on its purpose, may include several state variables since the ecosystem relations are very complex and interacted with each other.

3- Mathematical equations: are used to represent the biological, chemical and physical processes.

4- Parameters: are coefficients of mathematical representation of processes.

5- Universal constants: such as the gas constant, molecular weights etc.

According to the needs of the ecosystems, a suitable model should be selected to get best possible results with a few mistakes. Then, the right complexity of the model should be chosen to obtain maximum knowledge from existing data.

Models of ecosystems attempt to capture the characteristics of ecosystems. In a management context the problem to be solved can often be reformulated as follows: if certain forcing functions are varied, how will this influence the state of the ecosystem? The model is used to predict what will change in the ecosystem, when forcing functions are varied with time. The forcing functions under our control are often called control functions. The control functions in ecotoxicological models are for instance inputs of toxic substances to the ecosystems and in eutrophication models the control functions are inputs of nutrients. Other forcing functions of interest could be climatic variables, which influence the biotic and abiotic components and the process rates. They are not controllable forcing functions. The forcing functions are: outflows and inflows, concentrations of nitrogen components in the outflows and inflows, solar radiation, and the temperature, which is not shown on the diagram, but which influences all the process rates.

The Planning and Management of Lakes and Reservoirs program (PAMOLARE) encompasses two parts, namely database and ecological modeling. The database holds the information needed for the model that could eventually establish scenarios for the management of the Lakes. This program was provided by Prof. S. E. Jorgensen, and the modeling teams have been established by the experts from the relevant universities.

Planning and Management of Lakes and Reservoirs (PAMOLARE)

The model focuses on eutrophication and the PAMOLARE training software package was developed for use by decision-makers and engineers engaged in lake and reservoir management in developing countries and countries with economies in transition. This package allows for a better understanding of eutrophication processes in lakes and reservoirs.

The outlines of the 1-layer model

The 1-Layer model consists of a combination of two kinds of models: a causal dynamic model, and a set of associated empirical models. The dynamic model integrates the pools of nitrogen and phosphorus in water and sediment in time as functions of the mass flows. The empirical models are simple regressions made from data of simple physical and chemical characteristics of a number of lakes.

The dynamic model is a modification of the general model made by Vollenweider (1975). While Vollenweider's model was only concerned with phosphorus, which is the limiting nutrient in most freshwater bodies, Lake Model has included nitrogen as well. The nitrogen and the phosphorus sub models are almost identical. The only difference is the denitrification process included in the nitrogen sub model

The Outlines of 2-Layer Model

Enhanced phytoplankton growth (eutrophication) is a typical and serious problem encountered in many lakes and reservoirs all over the world. For better planning and management of water quality in lakes and reservoirs the important water quality parameters should be identified so that management strategies can focus on them when planning and simulating the future conditions of lakes and reservoirs under particular pollution levels. The vertical distribution of water quality should also be considered when describing the water quality in deep lakes and reservoirs where stratification occurs. Because the epilimnion and hypolimnion are rarely mixed in some lakes only limited water is transported through the thermocline during the stratification season. The typical phenomena observed during the day time in eutrophic lakes are super-saturation of dissolved oxygen, and depletion of inorganic nutrients and high concentrations of particulate matters in the epilimnion, and depletion of dissolved oxygen and high concentration of inorganic nutrients in the hypolimnion.

In this thesis, the 2-layer model consists of an upper layer of water (corresponding to epilimnion), and a lower layer of water (corresponding to hypolimnion). The water in each layer is assumed to be completely mixed, that is, the water quality in each layer is homogeneous.

The model proposed here is a fundamental model applicable to simulation of the changes in water quality in different lakes and reservoirs around the world.

Limitations of the model

The limitation of the model is that further hydrodynamic analysis of the reservoir can not be handled by the 1-layer and 2-layer models.

MAGICC and SCENGEN precipitation and temperature map generation

Model for the Assessment of Greenhouse-gas Induced Climate Change (MAGICC) and Global and regional climate change SCENario GENerator (SCENGEN) are the software packages that were used to generate the maps showing the predicted precipitation and temperature figures in the Southern African Region (Wigley *et al.* 2000). The policy scenarios used were:

a) SRESB1-which assumes a situation which will include, continued globalization and economic growth, and a focus on the environmental and social immaterial aspects of life. It describes a converging world. There will be rapid changes in economic structures towards a service of information economy, with reductions in material intensity and the introduction of clean and resource-efficient technologies.

Population stabilization is assumed (9 billion in 2050). A balanced government will exist for all nations and there will be a market in economic development. There will be an orientation in the non-material aspects of life and a convergence in income and the rapid diffusion of resource-efficient technology will persist.

There will be a strong focus on energy efficiency and sufficiency. A large preference for clean fuels will prevail and depletion in fossil fuels will cause their prices to rise thus further accelerating efficiency and zero carbon options to penetrate. Acceleration will be due to learning-by-doing. Lastly, there will be a rapid increase in the volume of trade in food and feed. (Source: http://arch.rivm.nl/image/scenario/A1.html).

b) SRESA2- Assumes a growing population (13.5 billion in 2100), slowdown in fertility decline with lower income. The focus will be on regional (cultural identity and the environment will be of low priority. The assumptions go on to include the lack of convergence in regional income and a slow diffusion of technology. Trade barriers are assumed to be present. There will be poor functioning markets and institutions in some regions.

On energy system dynamics, there will be a low rate of energy efficient innovations due to trade barriers and capacity scarcity. Coal use is projected to rise in many regions because it is seen as the cheapest available fuel as oil and gas become more expensive or unavailable. Capital intensive zero carbon options penetrate into most regions slowly. Lastly, will be a moderate increase in the volume of feed and trade in the food (Source: http://arch.rivm.nl/image/scenario/A1.html).

Working hypothesis

Models are not an effective tool for managing water resources

Alternate Hypothesis

Models are an effective water management tool and can be used to assist authorities to predict water quality when management practices are put into practice.

Objectives

This research is the first step towards the rehabilitation of Lake Chivero. The objectives of this research are basically:

- To predict the effect of a changing climate due to global warming on the water quality of Lake Chivero using the Model for Greenhouse Gas induced Climate Change (MAGICC) and identify the impacts they will have on water quality in the Upper Manyame catchment.
- To model scenarios in Lake Chivero's catchment using the PAMOLARE (Planning and Management of Lakes and Reservoirs) model and assess its effectiveness in water resource management.
- To provide solutions to the current eutrophication problem that are:
  -practical
  -workable, and
  -politically implementable basing on information generated from the above models.

  .

The overall objective is to assist local authorities in their efforts to prevent, reduce, and control the eutrophication of lakes and reservoirs through the application of sound management practices

Justification for doing the research

Lake Chivero is in a hypereutrophic state and as a result the condition it is in has bearing on a number of issues that affect the day-to-day lives of the citizens that rely on it for various uses:

- The catchment of the lake carries with it a population of approximately 2 600 000 people who rely on it the for drinking water purposes. Metabolic secretions from algae have been noted to have genetic impacts on mammals and were suspected to be the cause of gastro-enteritis in Harare (Zilberg 1966, Marshall 1991). Medical research found no explanation to this but they discovered that the outbreaks of the illness affected areas that got drinking water from Lake Chivero. It was also discovered that the period of illness also coincided with periods of algal blooms (Zilberg 1966). The health of the residents of the areas is thus at risk due to the eutrophic condition of the lake. Microcystins produced by *Microcystis aeruginosa* have been found to be hepatotoxic and also having sterility inducing, tumour promoting potential or carcinogenic effects (Irvine *et al.* 2002) as well as causing enlargement and congestion of the liver followed by necrosis and haemorrhage with possible neurotic activity (Carmichael 1994).

- Lake Chivero provides a fisheries industry to many people in the Harare and Norton area. It is thus a source of livelihood for a number of people. The situation in 1996 where several fish died (Moyo 1997), mostly green headed breams, *Tilapia rendalli*, is a cause for concern to both the livelihood of people as well as the general ecosystem functioning. Loss of fish species would thus affect the whole ecology of the lake in several ways.
- The tourism sector depends on facilities such as Lake Chivero and the surrounding National Park for drawing in revenue to both the City of Harare and the National coffers in terms of foreign currency through tourism. The current state of the lake is more of a deterrent to tourism as it provides an unpleasant sight as well as produces irritating odours that are produced by the decaying algae in the lake as well as the waste material that is transported into the lake from its catchment.,
- It is vital to know the fate of the lake under the current pollution situation. Modelling allows for different scenarios to be generated, viewing possible states of the lake. Effective management decisions may thus be made well in time to avoid disasters. The PAMOLARE model seeks to provide this option.
- The escalating costs of treating water have become a cause for concern to both the City Council and the residents, who have to pay huge water bills

to cater for these costs. Solutions have to be found to enable the cushioning of rate payer’s from these costs.

MATERIALS AND METHODS

Modelling using the MAGICC model

The model was used to predict precipitation and temperature changes in the Upper Manyame catchment for the 2000-2025 period. Two contrasting climate chance policy scenarios (SRES98A2 and SRES98B1) were used to predict the changes in climate for the period named. The reference scenario used was IS92a. Three climate sensitivity scenarios are possible for each prediction namely the high, medium and low range. When the model was run, the predicted changes are highlighted by a map of Southern Africa. To get a more accurate reading of the changes, the cursor was moved to the area covering the upper Manyame catchment under the Zimbabwe map. This resulted in the coordinates being reflected that cover the area under study, which were reflected on top of every map generated.

The values obtained were then used in calculations of water runoff (Precipitation readings) which would in turn affect the water residence time. Once the water residence time was calculated, this would then be inputted into the PAMOLARE model. For temperature readings, the same procedure was undertaken. When the readings were taken, these were then used as input data in the PAMOLARE model under the initial data input.

Modelling using the PAMOLARE model

In the PAMOLARE model, the 1-layer and 2-layer models were used. Data on the lake were collected from different sources (given below). These were inputted into the model to produce baseline data for use in comparison with simulations on water quality as a result of altering these initial readings.

For the 1-layer model, the parameters that were changed were those of:

- water residence time obtained from data produced from the MAGICC model. Different water residence times were used in the modelling process basing on the different changes occurring when runoff was altered due to different climate sensitivity scenarios.
- Phosphorous and nitrogen loadings:
    1. The effect of a changing population on water quality was projected by assuming a 3.5% per annum increase in population from 2004-2014. This was assumed to alter the loadings and thus proportions were used to calculate the future loadings using recently (2001) measured loadings provided by Nhapi (2004).
    2. The model was then used to view the effect of reducing loadings on Lake Chivero by implementing remedial measures. Several simulations were made and the best runs were then used to show the ideal loadings required to effect a turn around in the water quality of Lake Chivero.

For the 2-layer model, data obtained from the MAGICC model were used as input into the initial data composer in the PAMOLARE model. Data on temperature changes due to climate change were used and the effects of changing temperature on water oxygen levels were predicted by running the model under different water temperatures.

Lake Parameters

The various lake parameters that were used in the model were obtained from measurements done by:

1. Nhapi (2001, 2002) together with data he collected from July 2000 to December 2001. In this study, Nhapi collected water samples from 6 sites in Lake Chivero and the total nitrogen and total phosphorous values are averages form samples taken from all 6 sites. Flow rates were also obtained from Nhapi (2001).
2. Other measurements for the 2-layer model were derived from mathematical calculations that are explained in the PAMOLARE model. These are mean values obtained from extensive studies on many lakes around the world. They can be extrapolated to Lake Chivero and used without amendments.
3. Lake Morphology data were obtained from Thornton (1982).
4. Plankton measurements were taken from Ndebele’s (2003) Masters Thesis in which she sampled the lake in that particular year. Other plankton measurements were taken from Johansson and Olson 1999 and Robarts 1976.
5. Sediment chemical parameters were taken from Nduku 1976. However, adjustments were then made to match the current values in the lake by using proportions i.e. the

proportion of sediment-in the-Lake-to-nutrient values in the lake at the time to the current values of nutrients (Total-Phosphorous and Total-Nitrogen) to get the sediment phosphorous and nitrogen values.

RESULTS

The lake has two different phases during the year. In summer, the lake is stratified, i.e. it will be divided into two layers: the hypolimnion and the epilimnion. The second phase is the non-stratification phase, where the water is no longer in layers. The one-layer model is used for lakes which do not stratify because they are shallow. Stratification breaks down in lake Chivero thus at those times it can be treated as a single layer.

Precipitation changes in Upper Manyame Area and water residence time

Using the SCENGEN model, two contrasting scenarios (SRESB1 and SRESA2) can be used which will give different projections on the rainfall and temperature figures in the catchment. The assumptions that are used for each scenario are explained in Chapter 1.

The following are the SCENGEN generated maps of Southern Africa's projected precipitation changes by the year 2025. Three simulations were done on each scenario, that is, under: mid, high and low climate sensitivity ranges.

Note: The red rectangle in all SCENGEN maps represent the area covered by the Upper Manyame catchment where the values of change in precipitation were taken during the simulations. The co-ordinates on the map shows the area from which the readings were taken

High range climate sensitivity and percentage precipitation change

The following SCENGEN maps indicate the percentage precipitation change in the Upper Manyame catchment under scenarios SRESB1 and SRESA2 in the high climate sensitivity range:

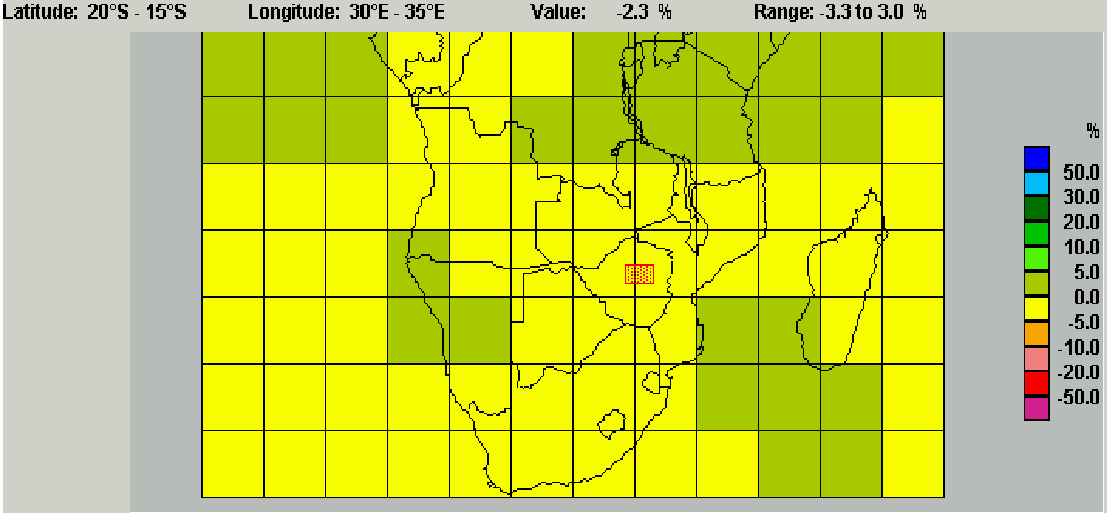


Fig 4: SCENGEN generated map of projected precipitation change in the high climate sensitivity range (SRESB1) for the Southern Africa region.

From the map above, it can be observed that the projected precipitation change will be -2.3% from the current figures. From calculations of inflows, it shows that the current average inflow rate into Lake Chivero of 680800m^3 (Nhapi *et al.* 2001) per day shall drop to 665141.6m^3 per day since runoff from the Lake's catchment will decrease. This implies that the residence time of water is set to increase from the current

1.6 years to 1.637years in the year 2025.

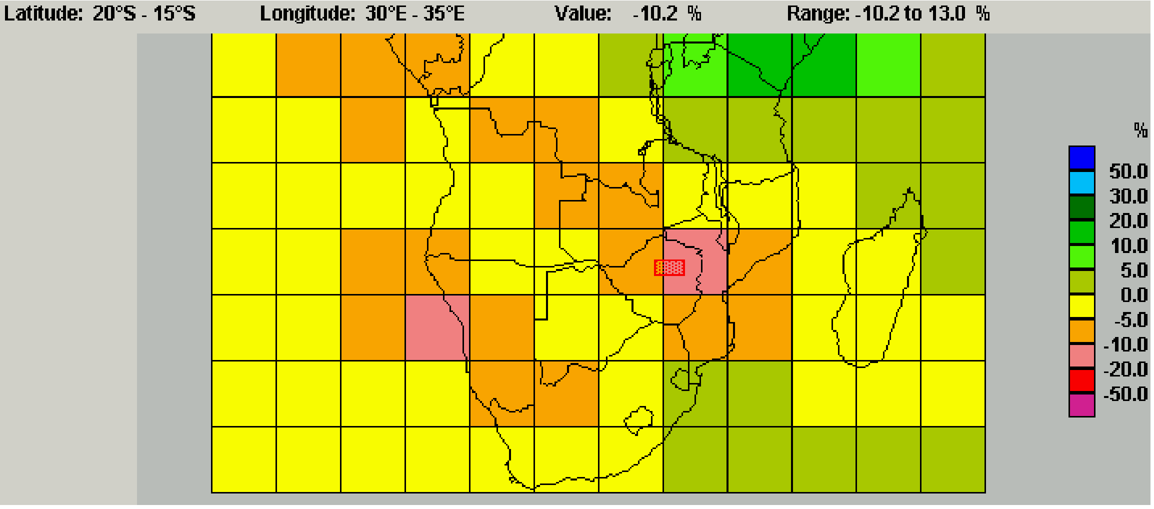


Fig 5: SCENGEN generated map of projected precipitation change in the high climate sensitivity range (SRESA2) for the Southern Africa region.

Under the above SCENARIO the precipitation figures in 2025 will be 10.2% lower than the current values. This implies a reduction in the water runoff into Lake Chivero to 611358.4m^3 per day. The residence period will be reduced to 1.782 years by the year 2025.

Mid range climate sensitivity and temperature change

The following are the SCENGEN maps that indicate the percentage precipitation change in the Upper Manyame catchment under scenarios SRESB1 and SRESA2 in the mid range climate scenario.

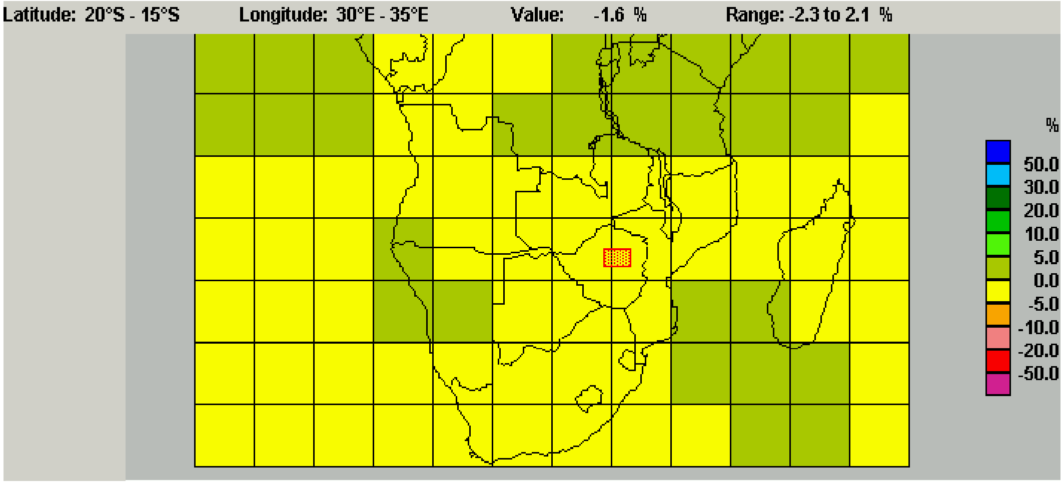


Fig 6: SCENGEN generated map of projected precipitation change in the mid climate sensitivity range (SRESB1) for the Southern Africa region.

In the mid climate sensitivity range, there is a projection of a -1.6% change in precipitation from the current precipitation figures. Runoff will be reduced and hence the average inflow into the lake will drop from 680800m^3 per day to 669907.2 m^3 per day. A corresponding change in water residence time will occur from the current 1.6 years to 1.626 years by the year 2025.

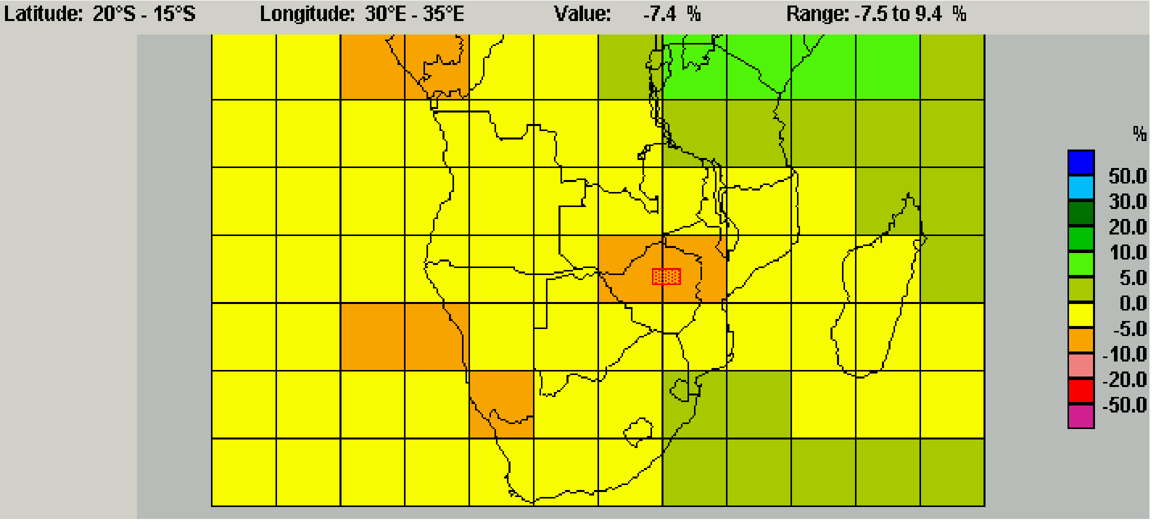


Fig 7: SCENGEN generated map of projected precipitation change in the mid climate sensitivity range (SRESA2) for the Southern Africa region.

A -7.4% change in current precipitation figures will result in a reduction of inflow into Lake Chivero to 630420.8m^3 per day from the current 680800m^3 per day. This will result in a corresponding change in water residence time to 1.728 years from the present 1.6 years.

Low range climate sensitivity and percentage precipitation change

The following are SCENGEN maps that indicate the percentage precipitation change in the Upper Manyame catchment under scenarios SRESB1 and SRESA2 in the low climate sensitivity range.

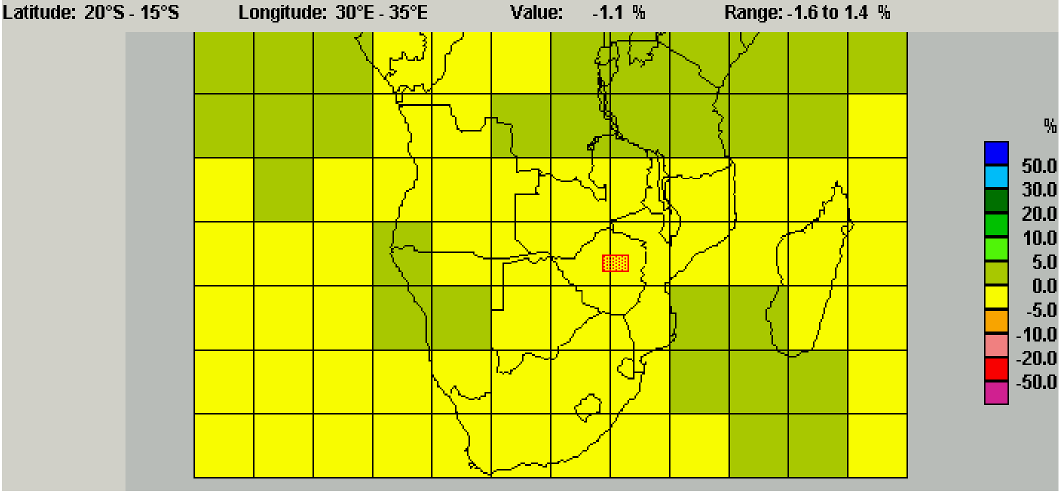


Fig 8: SCENGEN generated map of projected precipitation change in the low climate sensitivity range (SRESB1) for the Southern Africa region.

The reduction of precipitation by 1.1% will lead to the reduction of inflow into Lake Chivero to 673311.2m^3 per day. A corresponding decline in water residence time will occur to 1.618 years from the current 1.6 years.

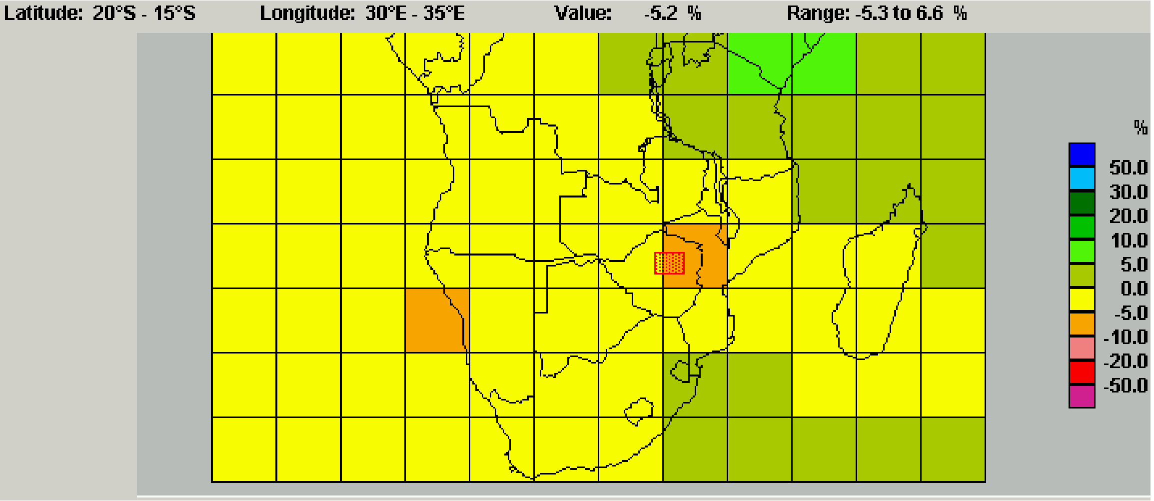


Fig 9: SCENGEN generated map of projected precipitation change in the low climate sensitivity range (SRESA2) for the Southern Africa region.

The above map shows a -5.2% change in the current precipitation, by 2025, resulting in a drop in water inflow to Lake Chivero to 643598.4m^3 per day from the current 680800 m^3 per day. The change will result in an increase in water residence time to 1.692 years.

Under the current situation, which is explained by the reference scenario IS92a, the projected phosphorous and nitrogen levels in Lake Chivero will be as follows:

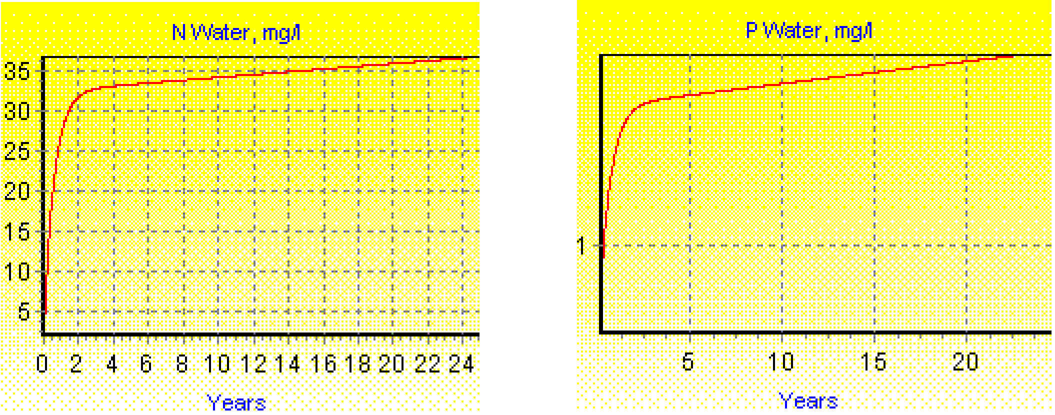


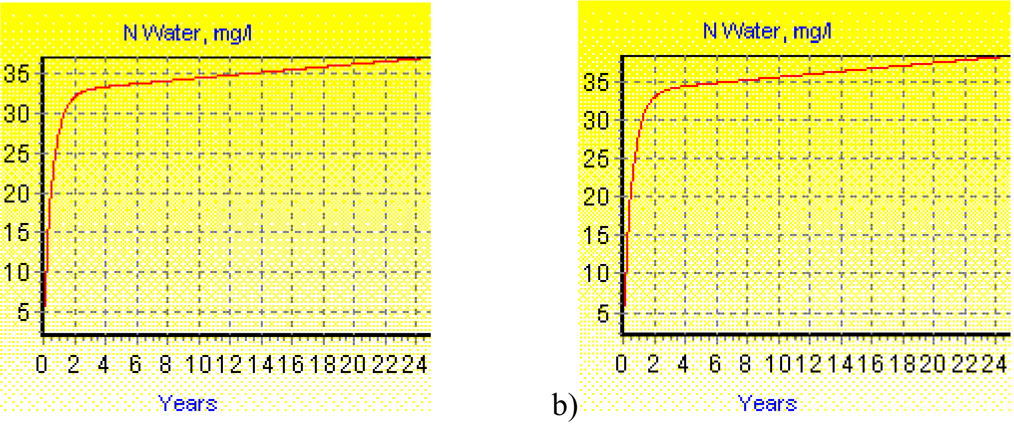
Fig 9b: PAMOLARE projections of nitrogen and phosphorous levels in Lake Chivero in a business as usual situation using reference scenario IS92a

The above is a simulation under the business as usual situation where the current loading figures remain the same and residence time remains at 1.6 years. This figure can be compared to the following projections under the policy scenario SRESA2 and SRESB1 which show changes in the current rainfall and temperature changes due to climate change.

Effect of increasing residence time on lake biology and chemistry

From the maps above, the effect of changing the water residence time on the water chemistry can be observed by running PAMOLARE simulations for a 25 year period from the year 2000 to 2025.

Effect of high range climate scenario on water biology and chemistry



a) b)

Figure 10: PAMOLARE simulations on the effect of changing water residence time on nitrogen levels using: a) SRESB1 to 1.637 years and b) SRESA2 to 1.782 years from the current 1.6 years.

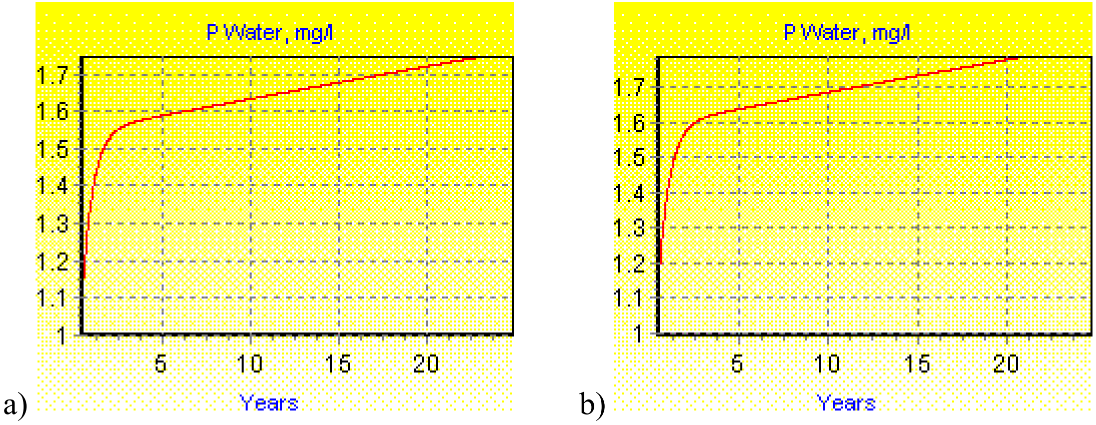


Figure 11: PAMOLARE simulations on the effect of changing water residence time on phosphorous levels using: a) SRESB1 to 1.637years and b) SRESA2 to 1.782 years from the current 1.6 years.

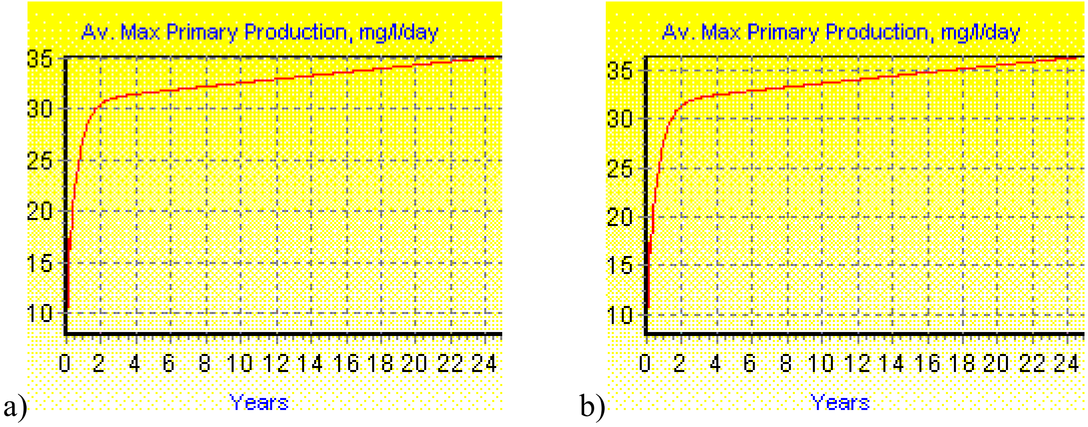


Figure 12: PAMOLARE simulations on the effect of changing water residence time on primary production using: a) SRESB1 to 1.637years and b) SRESA2 to 1.782 years from the current 1.6 years.

A change in precipitation in the high range climate scenario shows a faster rate of increase in total phosphorous and total nitrogen in water for scenario SRESA2 than SRESB1. As a result, the average maximum primary productivity is higher for a change in residence time to 1.782 years than for 1.637 years. Lake Chivero is set to be more productive under the assumptions of scenario SRESA2 than under those of SRESB1.

Effect of mid range climate scenario on water biology and chemistry

The Pamolare projections of the water chemistry under the mid range climate scenario for the 2000-2025 period are as follows:

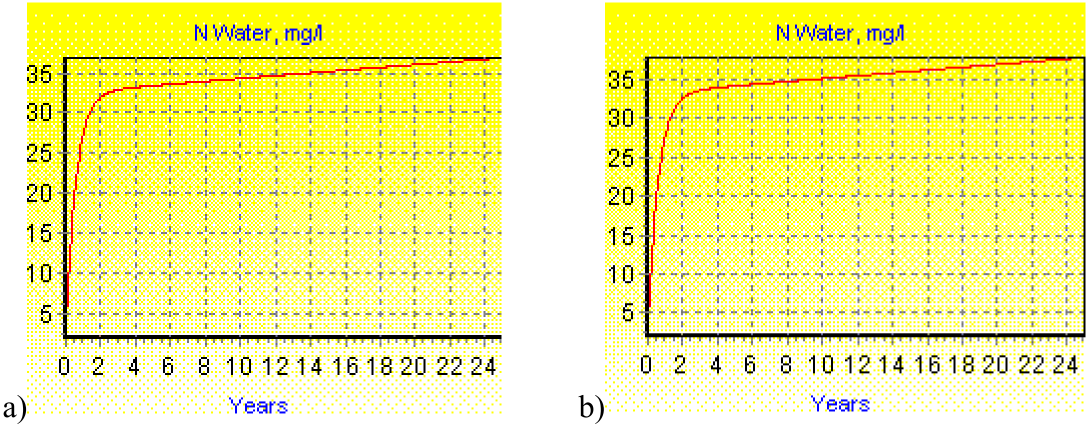


Figure 13: PAMOLARE simulations on the effect of changing water residence time on nitrogen levels using: a) SRESB1 to 1.626years and b) SRESA2 to 1.728 years from the current 1.6 years.

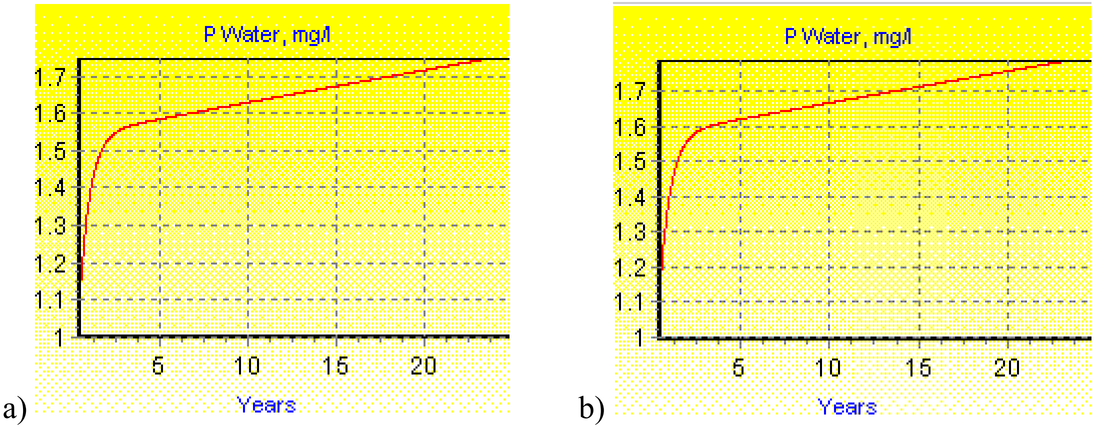


Figure 14: PAMOLARE simulations on the effect of changing water residence time on phosphorous levels using: a) SRESB1 to 1.626years and b) SRESA2 to 1.728 years from the current 1.6 years.

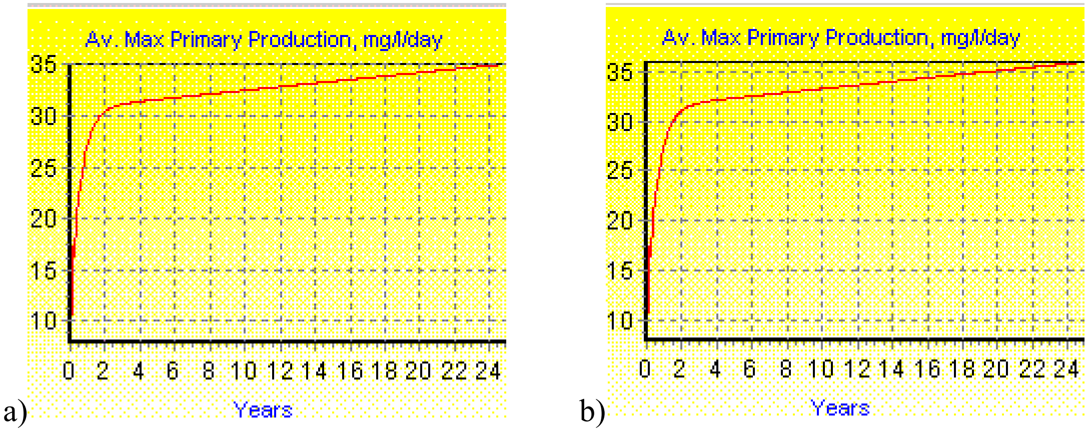
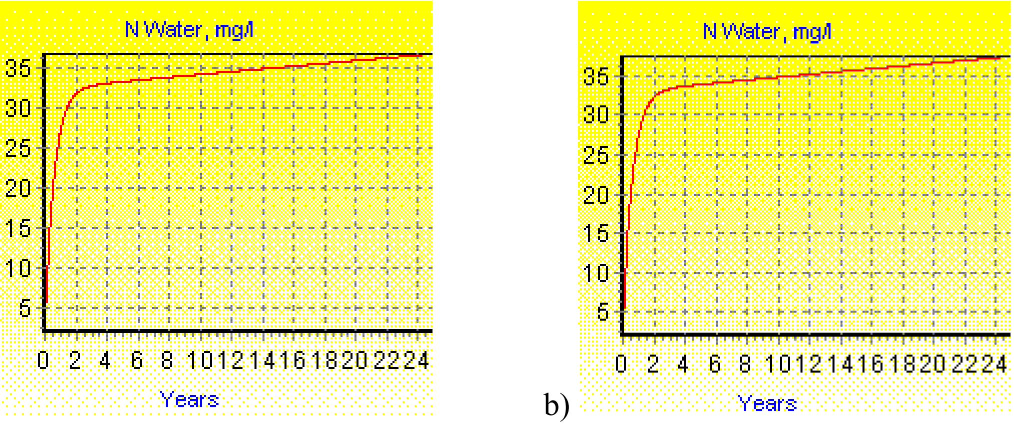


Figure 15: PAMOLARE simulations on the effect of changing water residence time on primary production using: a) SRESB1 to 1.626years and b) SRESA2 to 1.728 years from the current 1.6 years.

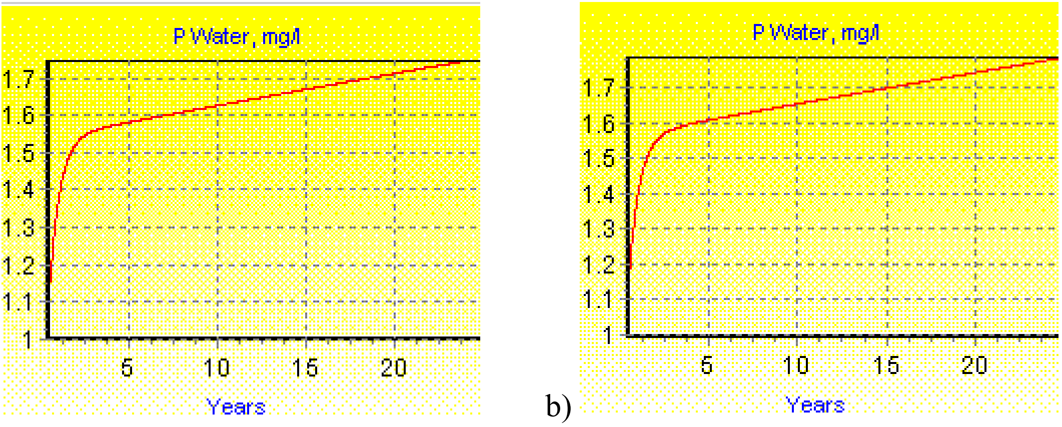
The change in precipitation, and consequently residence time, caused by the conditions assumed by scenario SRESA2 are set to produce a more eutrophic Lake Chivero than the conditions assumed by scenario SRESB1. This implies a higher average maximum primary productivity under the more severe scenario (SRESA2) than SRESB1.

Effect of low range climate scenario on water biology and chemistry



a) b)

Figure 16: PAMOLARE simulations on the effect of changing water residence time on nitrogen levels using: a) SRESB1 to 1.618years and b) SRESA2 to 1.692 years from the current 1.6 years.



a) b)

Figure 17: PAMOLARE simulations on the effect of changing water residence time on phosphorous levels using: a) SRESB1 to 1.618years and b) SRESA2 to 1.688 years from the current 1.6 years.

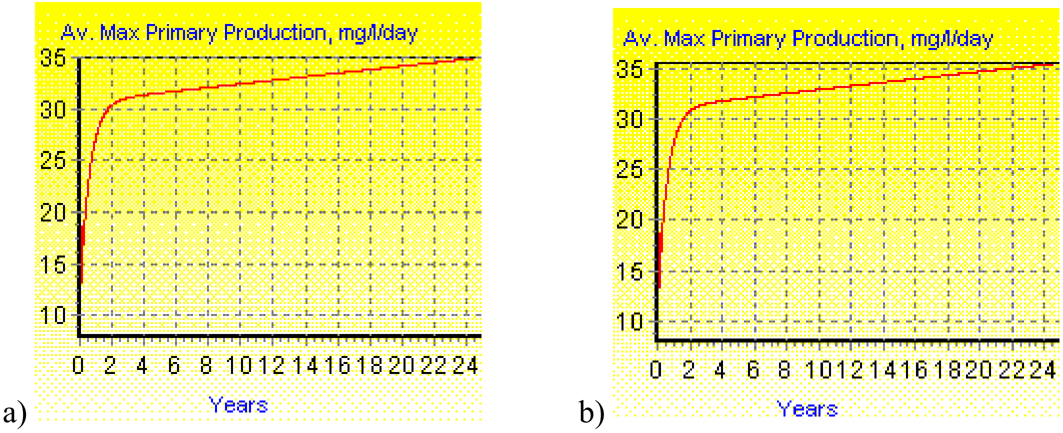


Figure 18: PAMOLARE simulations on the effect of changing water residence time on primary productivity using: a) SRESB1 to 1.618 years and b) SRESA2 to 1.688 years from the current 1.6 years.

The low range climate scenario shows the least impact on Lake parameters among the 3 climate sensitivity scenarios. However, despite the relatively lower levels of nutrients in the lake, the lake will still have high nutrient levels according to the water quality standards.

From all the PAMOLARE simulation carried out above (from the high range to low range scenarios) there is the assumption that loading of nutrients into the lake from its catchment remains the same as the current levels.

From all the simulations above, there is an indication that the water clarity is set to decrease due to increased productivity of the lake. The secchi depth therefore will decrease. The figure below gives an indication of how the secchi depth will decline over the next 25 years in the worst case scenario under the high climate conditions using the SRESA2 assumptions:

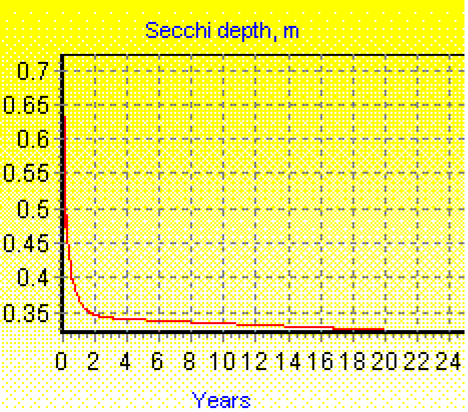


Figure 19: PAMOLARE projections of the Secchi depth in Lake Chivero over the next 25 years.

If the secchi depth decreases to the extents that the graph above shows, the water will be virtually overloaded with plankton. This will result in a reduction in the aesthetic properties of the lake and at the same time the portability of the water will be reduced. The visibility in the water will be greatly reduced resulting in fish species in the lake being affected especially those species that migrate to the shallow parts of the lake to breed.

Climate change and water temperature changes in Lake Chivero

The water quality can be altered by changing the temperature of the water in a lake. Under both emissions scenarios SRESA2 and SRESB1, similar outputs were observed on the projected temperature change by the year 2025. The following are SCENGEN generated maps showing the projected atmospheric changes in temperature in the Upper Manyame catchment:

High range climate scenario for both SRESA2 and SRESB1

The upper extremes of projected temperature changes are shown by the following maps

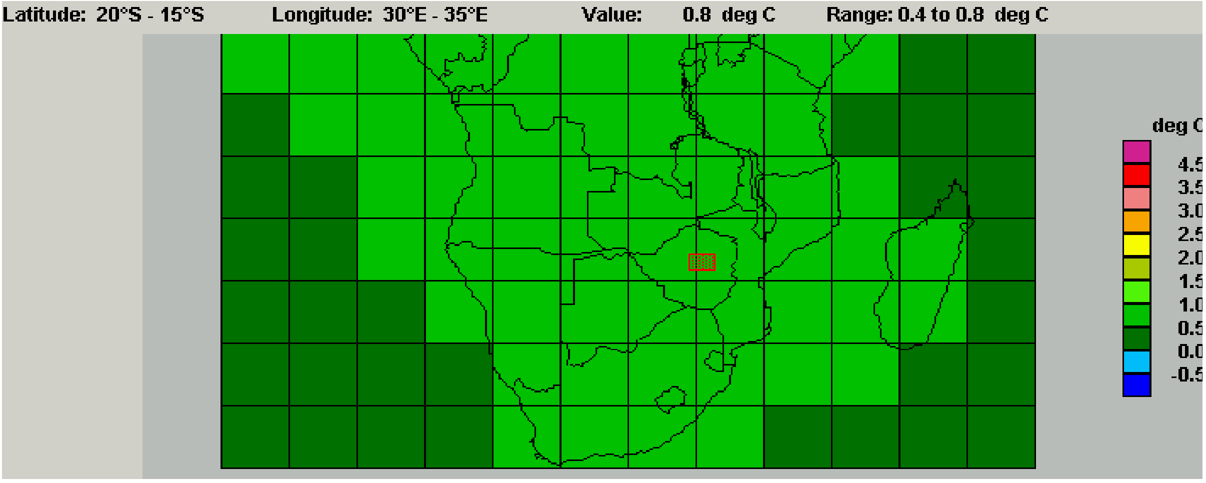


Figure 20: SCENGEN generated map on temperature change in Upper Manyame area by the year 2025 in the mid climate sensitivity range

The simulation predicted a 0.8°C rise in temperature. This is the maximum temperature increase that can be expected in the Upper Manyame catchment according to the simulations.

Mid range climate scenario for both SRESA2 and SRESB1

The following map shows the intermediate range of temperature change in the Lake Chivero area that can be expected by the year 2025 under the above mentioned scenarios.

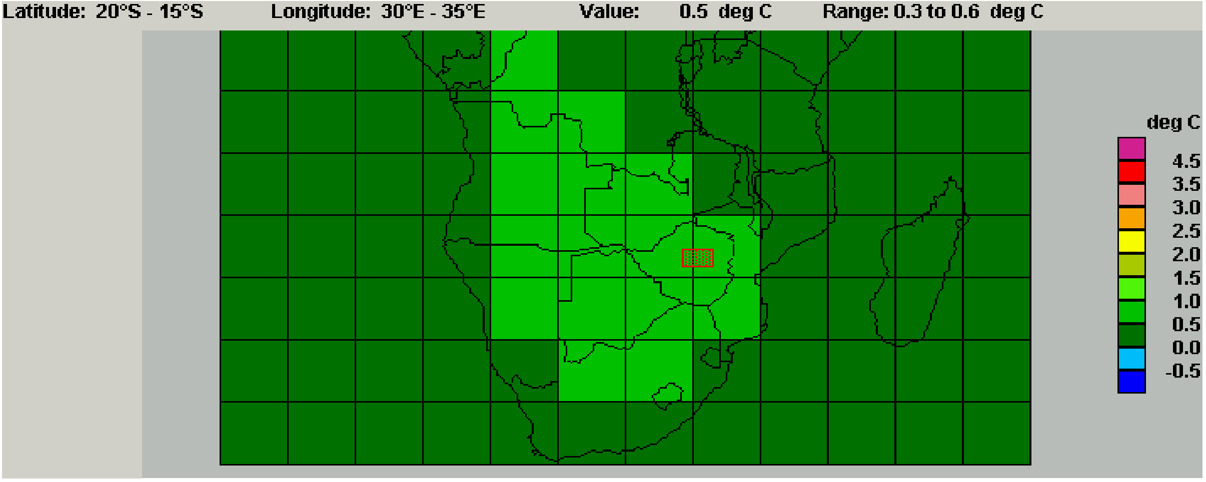


Figure 21: SCENGEN generated map on temperature change in Upper Manyame area by the year 2025 in the mid climate sensitivity range.

The simulation predicted a 0.5^{0}C increase in atmospheric temperatures compared to the current temperatures.

Low range climate scenario for both SRESA2 and SRESB1

The lower extreme of the expected temperature changes are represented in the map below:

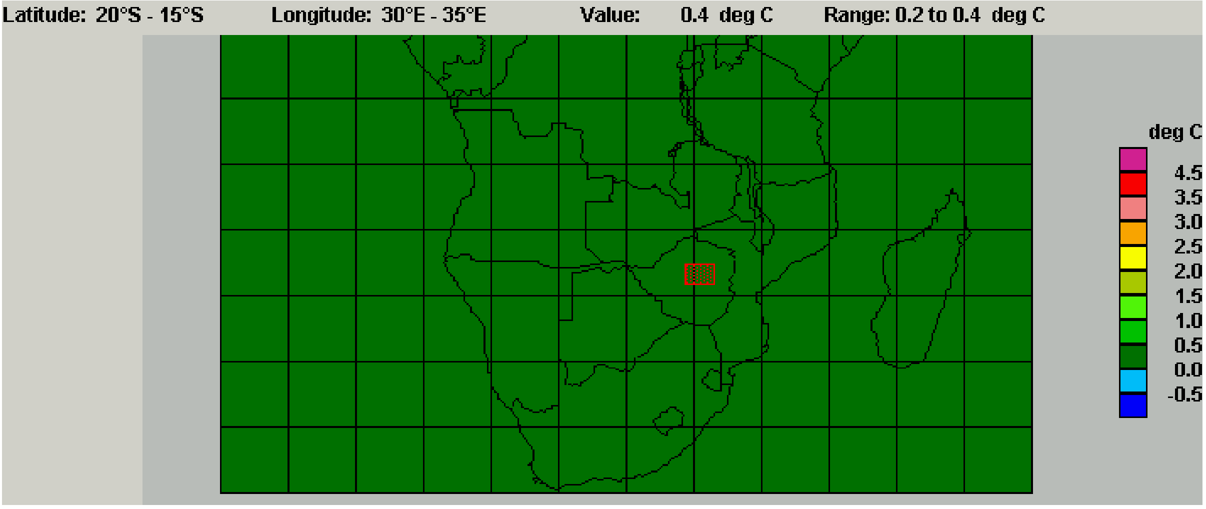


Figure 22: SCENGEN generated map on temperature change in Upper Manyame area by the year 2025.

From the 3 maps above, it is evident that the high climate sensitivity range gives the greatest increase in temperatures. On the whole, the projections show an increase in the atmospheric temperatures over the Southern Africa region. These changes in temperatures will have an impact on the lake's chemistry. The following section shows one of the effects of changing water temperature on water chemistry.

Two-layer simulations of effect of temperature change on water oxygen levels

The two layer model has been used to show the effects of increasing global temperatures on the water oxygen levels under all three climate sensitivity ranges. The graphs show the levels of oxygen in both the hypolimnion and epilimnion under: a) the current temperatures (represented by the blue lines) and b) when the water temperatures are altered (represented by the red and green lines on the graphs).

Effect of changing water temperatures under high climate sensitivity

Fig. 20 predicts a 0.8^0C rise in temperature in the Upper Manyame area. The effect on the water chemistry is shown below:

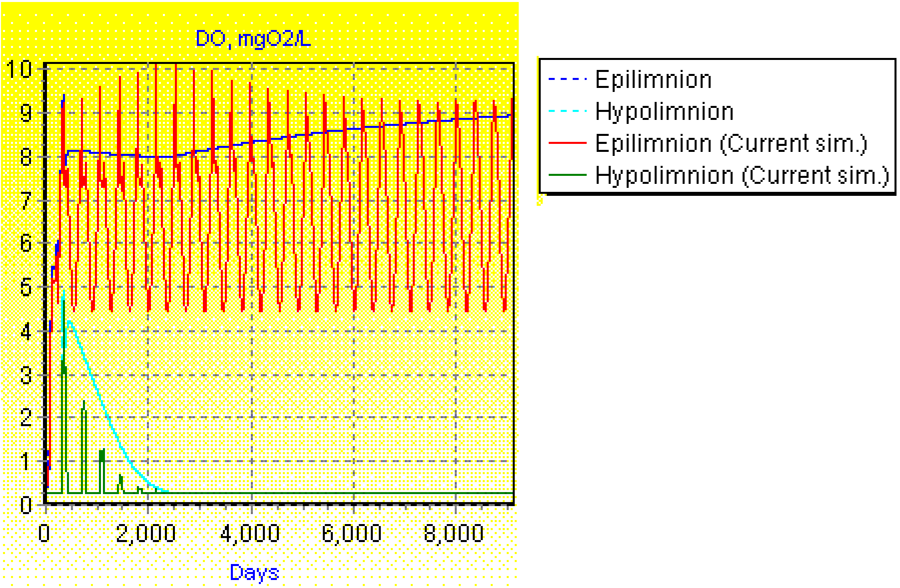


Figure 23: Effect of changing the annual water temperature by 0.8°C on lake oxygen levels

Climate change under both SRESA2 and SRESB1 predict a 0.8°C rise in temperature by the year 2025. The effect on the lake as seen above is of a lowering of the lakes oxygen levels over time. In the epilimnion the oxygen levels will fluctuate between 4.5mg/l and 10mg/l. In the hypolimnion the levels of oxygen are set to decline to levels close to 0mg/l thus the layer becomes anoxic.

Effect of changing water temperatures under mid level climate sensitivity

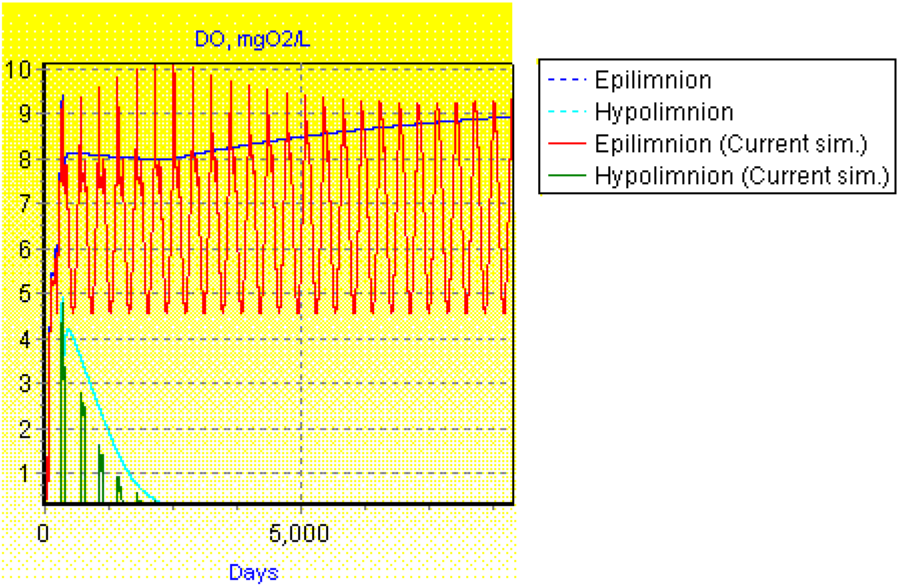


Figure 24: Effect of changing the annual water temperature by 0.5°C on lake oxygen levels

The results observed from the graph above are similar to that of changing the water temperature by 0.8^{0}C except that the levels of oxygen in the hypolimnion will be higher. However, the lake will have anoxic conditions in the hypolimnion, as is the case in the former scenario.

Effect of low climate sensitivity to water chemistry

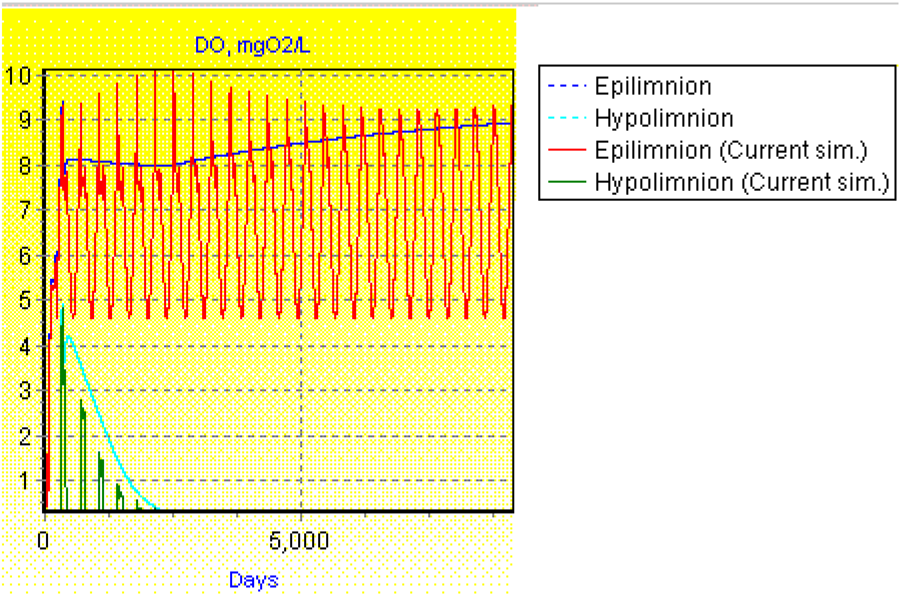


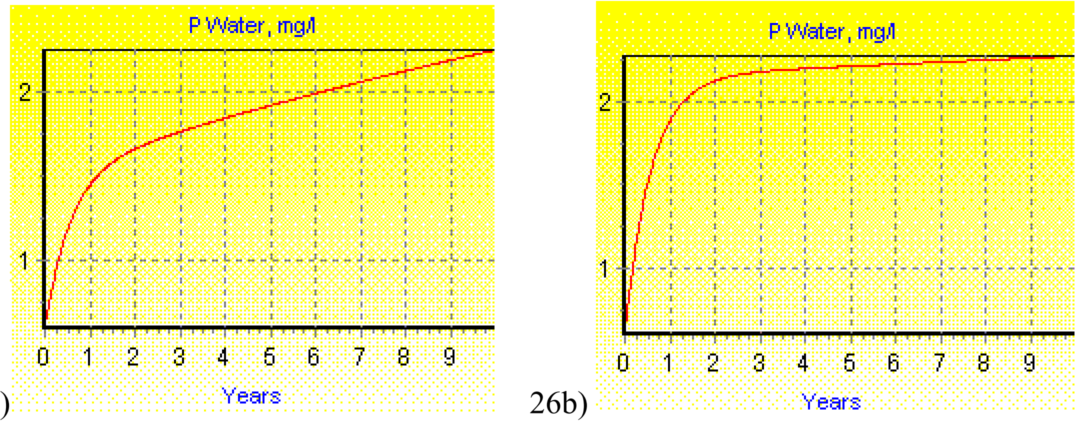
Figure 25: Effect of changing the annual water temperature by 0.4°C on lake oxygen levels

Under a low climate sensitivity, the oxygen levels will decline but at a slower rate than both the mid and high climate sensitivity scenarios.

From all the graphs above, there is a clear indication that the oxygen levels in the lake will on average decline. The hypolimnion will become anoxic after about 2 years thus rendering the water in the hypolimnion uninhabitable to organisms that require oxygen to respire.

Population growth and consequences on the Lake

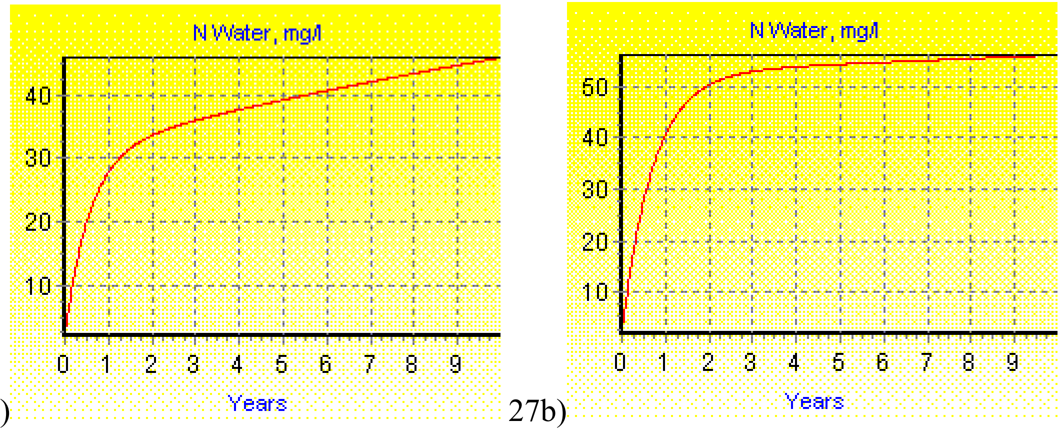
The rate of increase of the population of Harare and its surrounding areas is estimated to be about 3.5% per annum. In the next 10 years the population of the City will thus be approximately 2 685 089. With such an increase in the number of people, the amount of wastewater the city produces is also set to increase, assuming no infrastructural adjustment are done to cater for the increases. As a result, the nutrient loadings into Lake Chivero are set to increase proportionately. The following are simulations of 10 years projections of Lake Chivero's water quality under a larger population (assuming no development of infrastructure occurs to cater for the growing population):



26a) 26b)

Figure 26: PAMOLARE projections of phosphorous levels if population a) remains constant and loading remains at 24.4g/m^2/yr and b) increases by 3.5% and increasing loading to 34.42g/m^2/yr over the 2000-2010 period.

Projections show an increase in phosphorous levels in Lake Chivero following a 3.5% population increase per annum in the next 10 years. Fig 26b shows that the rate of increase of phosphorous will be higher than what is projected under a constant population. This implies that the levels of nutrients in the lake will be higher. Water quality will thus deteriorate at a higher rate when population growth occurs. The same applies for the nitrogen levels in the lake as evidenced by Fig. 27 below:



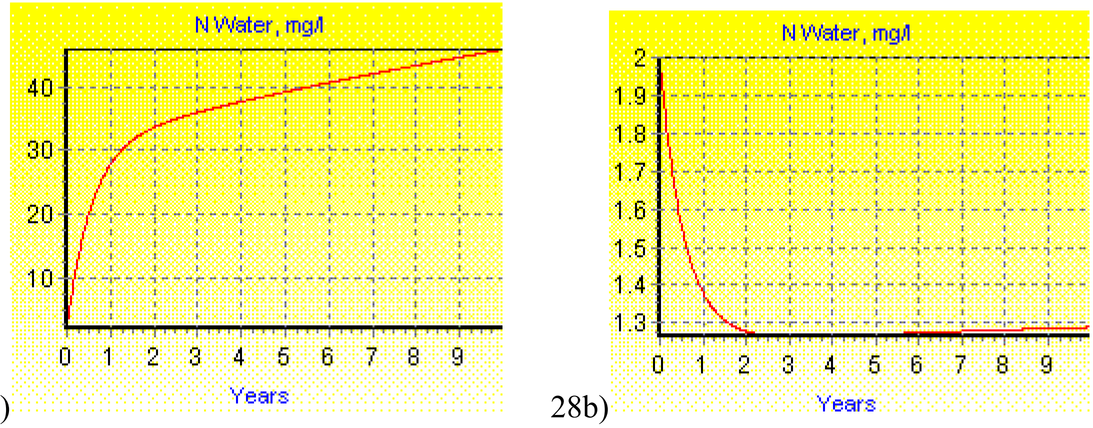
27a) 27b)

Figure 27: PAMOLARE projections of nitrogen levels if population a) remains constant and loading remains at 108.9g/m2/yr and b) increases by 3.5% and increasing loading to 153.61g/m2/yr for the 2000-2013 period

From Figs. 26 and 27 above, it is evident that the rate at which the nutrient levels in the lake increase is higher when the population increases. After a year, the levels of nutrients will have shot up to higher levels than the scenario that will occur if the population remains the same.

Modelling as a remediation tool using the one-layer model

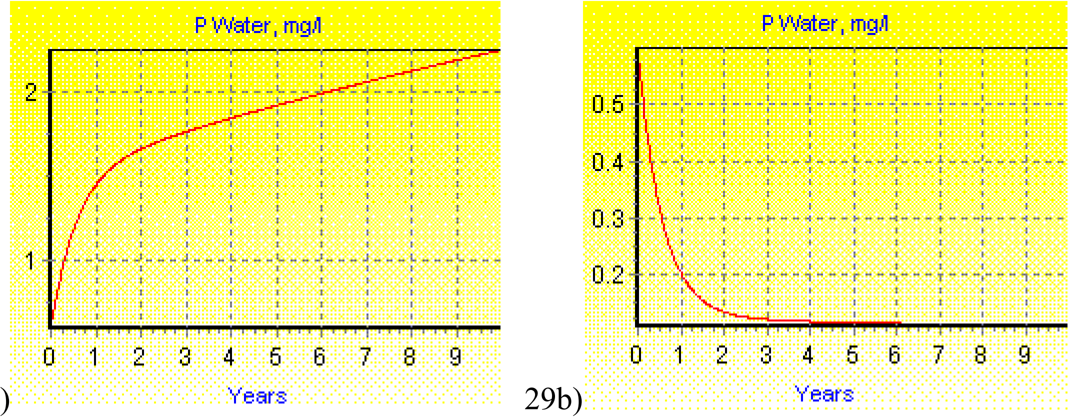
The model allows for the simulation of different nutrient loading scenarios in the lake. This tool can thus be used to implement changes and cause a turn around in the lakes fortunes. The following figures show the effect of reducing the loading of nitrogen and phosphorous in the lake:



28a)

28b)

Figure 28: PAMOLARE simulation of lake chemistry if total phosphorous: a) loading remains at 108.9g/m^2/yr and b) loading is reduced to 2g/m^2/yr.



29a) 29b)

Figure 29: PAMOLARE simulation of lake chemistry if total phosphorous a) loading remains at 24.4g/m^2/yr and b) loading is reduced to 0.5g/m^2/yr.

The two figures above show how reduction in the nitrogen and phosphorous loadings in Lake Chivero will affect the lakes chemistry. If these values are attained, the lake will transform into a mesotrophic-oligotrophic state resulting in an improvement of water quality. Primary productivity will be greatly reduced as seen in Fig. 30 below:

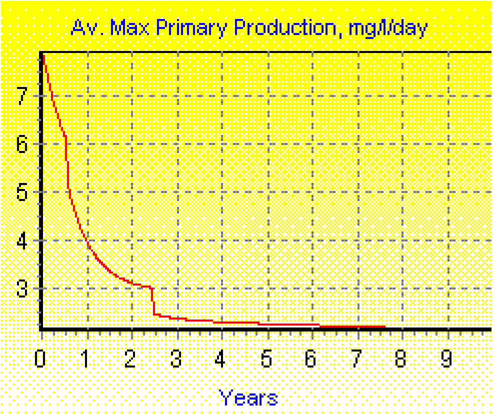
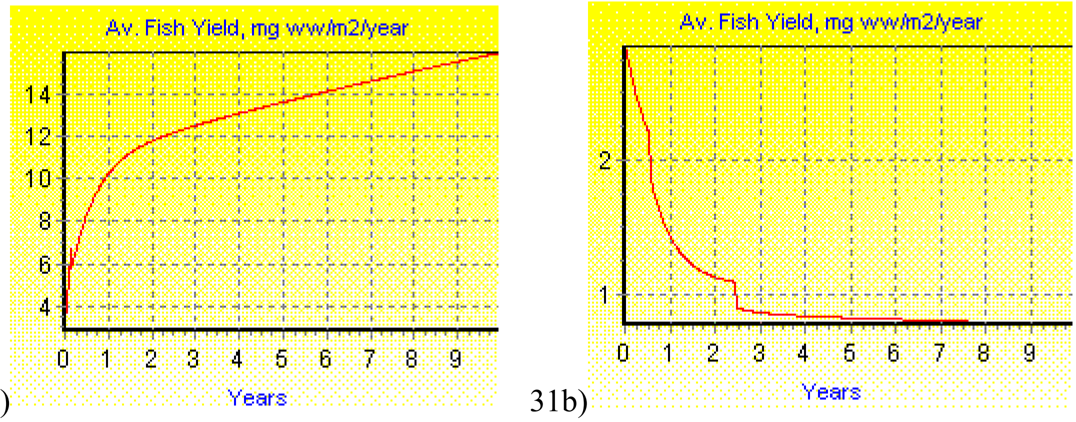


Figure 30: PAMOLARE simulations showing the average maximum primary production in Lake Chivero upon reduction in nitrogen and phosphorous loadings to 2 and 0.5g/m^2/yr. respectively.

If loadings are reduced to the levels mentioned above, the productivity of the lake will decline significantly. The biomass in the lake will decline as the nutrients that they utilise, directly or indirectly to propagate will be reduced. The figure below shows the change in fish production that occurs as a result of reduction of nutrients entering the lake compared to the scenario that will occur if the loadings remain as they are presently:



31a) 31b)

Figure 31: PAMOLARE simulations of fish yields in Lake Chivero if a) nitrogen and phosphorous loadings remain at 108.9 and 24.4g/m2/yr respectively and b) nitrogen and phosphorous loadings are reduced to 2 and 0.5g/m2/yr respectively.

Since the productivity of the lake is reduced as a result of reducing the loadings, the fish yields will drastically decline as the food in the form of phytoplankton and zooplankton will have declined as nutrients will have been reduced to very low levels.

DISCUSSION

From the results, it is evident that modelling is an effective tool in managing water resources. Results obtained from the MAGICC model, show the two contrasting scenarios will bring different levels of climate change and these will have different impacts on Lake Chivero's water quality. Water residence time was shown to be an important parameter which was shown to be affected significantly by reduced runoff as a result of reduced precipitation in the Upper Manyame catchment. The co-ordinates show a significant level of accuracy since they coincide with those of Lake Chivero. Management of water resources can thus be effected using such a tool since it provides the managers with some foresight which could lead to measures being taken that could counter the effects of reduced water supplies resulting from climate change.

By comparing the two contrasting climate change scenarios, it is evident that SRESA2 has a greater impact on the climate than SRESB1. As a result, it is an indicator of how much impact human activity will have if they follow the assumptions under the former scenario.

Although the two scenarios differ on their impact, it was shown that both have a negative impact on the water quality (though indirectly). As a management tool, it is thus effective as it can be used to enforce a change in attitudes of people involved. It is however a global attitude change that will be required rather than just the Upper Manyame catchment alone.

The PAMOLARE model can also be used as an effective management tool as it showed important water parameters that have a significant impact on water quality. It was shown that the projections done using the model can be used to enforce remedial measures before the projected water quality measurements are reached. As a management tool this is important since it gives managers ample time to react to nutrient loading in the Lakes catchment. It was shown in Figs. 28-30 that the moment positive changes are made to nutrient loads there is an improvement of the Lakes water quality in a reasonable time scale. These changes in nutrient loadings can be achieved and the following are some of the proposals that have been put across by Nhapi (2004):

In order to achieve loadings of $2g/m^2/yr$ and $0.5g/m^2/yr$ for Nitrogen and Phosphorous respectively, the following areas are supposed to be looked at:

- The sewage works that have been mentioned in Table 1 should be upgraded to enable efficient treatment of sewage resulting in the release of water that meets the stipulated levels. This is an important area to look into since it produces a high percentage of waste water that enters Lake Chivero's feeder rivers. The percentage overload of the sewage ponds are Crowborough (98%), Firle (6%), Marlborough (450%), Donnybrook (64%), Hatcliffe (60%) (Nhapi 2004). The total percentage overload of the wastewater treatment plants is 36%. These facilities need to be upgraded to enable efficient wastewater treatment.
- The major sources of water pollution upstream of the wastewater treatment plants (WTP) are storm water drainage and illegal point source discharges. Storm water drainage in the catchment flows into rivers without undergoing any treatment process. There is a need to control the amount of nutrients that are received by rivers by treating storm water before it enters these rivers as well as ensuring that garbage collection is done efficiently thus reducing the amount of material that is washed away from the streets.

- The current pasture land available for irrigation is 1400ha. Nhapi (2004) argues that this is insufficient and 6730ha is required for handling the current load of 196000m^3 of effluent. Increasing the area that is irrigated would help reduce more nutrients from the wastewater received from the sewage treatment plants. Furthermore, harvesting grass at the pasture lands and removing cow dung can be done as methods of exporting nutrients. This therefore improves resource recovery (Nhapi 2004).

Nhapi (2004) also proposes a 3 phase improvement of wastewater management which involves:

1. Short term (0-5yrs) - Focusing on implementation of water saving measures and pollution prevention and control
2. Medium term (5-10yrs) - Focusing on pollution control.
3. Long term (over 10 yrs) - Focusing on increased resource recovery and reuse.

Although the current nitrogen concentrations in effluent from the Upper Manyame catchment conform to the standards set out by the Standards Association of Central Africa (1972), those of phosphorous are violating the regulations. The effluent discharges into sensitive waters are set out at 10mg/l (TN) and 0.5mg/l (TP) (Government of Zimbabwe S.I. 274 of 2000). Future population projections indicate a higher population than that of the present. An increase will thus result in a change in nutrient loadings which will lead to the breaching of these standards (see Figs. 26 and 27) in both nitrogen and phosphorous concentrations. Since projected population figures will overburden the existing infrastructure, corrective measures have to be put in place immediately to avoid this from occurring. There is need for a complete overhaul of existing infrastructure that treats wastewater since the current infrastructure is underdesigned (see Table 1). Planners need to move away from working with current population figures to using projected numbers to avoid the issue of underdesigning. Magadza (2004) states that the emerging problem of loading in inland waters is that of unmonitored diffuse source runoff and that the short doubling period for urban populations of 15.4 years requires the upgrading of facilities on the average every 1.5 decades.

Nhapi (2004) states that the BNR effluent from Crowborough is of good quality (4.6±3.0mg/l TN, 0.7±0.6mg/l TP). On the other hand the BNR effluent form Firle is poor (13.7±10.7mg/l TN, 1.9±3.4mg/l TP). This is mainly due to plant breakdowns and poor maintenance. There is thus need for proper maintenance of facilities by the responsible authorities in order for a turnaround in water quality to be observed. Furthermore, the maximum allowable limits of 0.1mg/l TN and 0.03mg/l TP for avoiding excess plant growth in rivers (OME Guidelines 1991) are being exceeded. The allowable limits of 0.3mg/l TN and 0.01mg/l TP for drinking water in lakes (Mandaville 2000) are also being exceeded. The hydraulic overload of wastewater treatment plants has been related to high water consumption (Nhapi 2004). Upgrading wastewater treatment plants to match inflows will aid in reducing the current nutrient levels to permissible levels.

Nitrogen and phosphorous are the important nutrients that stimulate growth of aquatic plants. These are important for the food chains in an aquatic system since they are the primary producers. However, over production of algae and other aquatic organisms can result in negative impacts on the lake environment. Fig 19 shows how rapid algal growth will affect the visibility of the water as the secchi depth is reduced with time.

Dense masses of algae result in high competition for nutrient and sunlight leading to the early death and decay of these photosynthetic species. Oxygen levels in the epilimnion will thus be depleted as decay of the dead material takes up a lot of oxygen. This further affects other aquatic life as the oxygen tensions become low. On the whole, the environment will not be conducive for life.

Figure. 31a shows the effect of increased productivity in the lake on fish yields. Though this is a positive development on the economic and subsistence side of things, this could also mean that there will be severe competition for resources such as oxygen between plant and animal life leading to deaths in numbers of these fish especially at night when both are consuming oxygen during respiration.

From the results, modelling was used to find what parameters are important and which of these should be changed to see a turn around of the lake from a hypereutrophic state (0.145-0.545mgP/L) to an oligotrophic state (0.012-0.047mgP/L). If the recommendations that come out from the results obtained from the modelling exercise are followed, the trends that are seen in Figs 28b, 29b and 30 can be realised in the projected time frame as long as the remedial measures are implemented consistently.

Not to be overlooked is the issue of other chemicals besides phosphorous and nitrogen. Mercury, arsenic, lead, PCB’s just to mention a few are more fatal to human health than phosphorous and nitrogen. The release of such deadly chemicals by industries should also be looked into as these have more severe consequences on human health. All chemical discharges into Lake Chivero should conform to the set limits regardless of who is releasing them. Government industries should set the trend so that others can emulate positive steps done by them (e.g. ZIMPHOS).

The salinity of Lake Chivero is an illustration of human impact on fresh water resources (Magadza 2004) and the increase in salinity over the years has been attributed to increased water return from the City of Harare (Magadza 1997). There is an increase in the proportion of return water into public streams in an environment of increasing water stress.

The graphs in the results clearly showed that with changes can be realised within 5 years of implementing remedial measures. Similar results were observed in the late 1970's when the then Salisbury City Council implemented remedial measures that involved diverting sewage to pasture lands. It gives an indication that there is hope for the hypereutrophic lake.

Lake Chivero has an advantage over larger lakes such as Lake Victoria in that it has a short water residence time. The latter has a water residence time of about 260 years (Magadza pers. Comm.) and thus remediation will take longer to produce desired results in Lake Victoria than in Lake Chivero.

The following are possible solutions or measures that can be implemented be responsible authorities to achieve the objective of seeing a turnaround in the fortunes of Lake Chivero:

Recommendations to possible solutions to the eutrophication problem

A number of solutions can be put forward to help reduce or manage the pollution that has led to the eutrophic status of Lake Chivero. It should be kept in mind that a zero pollution option is not an option for a third world country like Zimbabwe and efforts should be made to reduce pollution or emission levels to sustainable levels rather than attempt to stop it altogether. This will have severe impacts on industries and subsequently on the economy since most of the polluting industries cannot put in place on-site water treatment equipment to regulate their emissions or discharge.

Of particular importance in addressing lake and reservoir problems is the need to consider an “ecosystem approach”. Here, rather than adopting the sectoral approach that focuses on a single water use, the ecosystem approach considers both human water needs within the larger context of the drainage basin and environmental water needs or ecological requirements. This approach, therefore, is a prudent means of balancing the water needs for economic development and environmental protection.

There has been a misconception that the only way to prevent the problem is through the use of technology. Technology can assist in this endeavor, but it is not the only answer.

There are several ways in which individuals to organisations can act to prevent polluting the lake:

Seeking alternative water sources

The Kunzvi Dam project has been talked about for almost a decade but there has been no progress to this project. The dam, to be built at the confluence of Nyagui and Nora Rivers in Goromonzi district falls in a different catchment area from Chivero, Manyame, Seke and Harava dams that derive their water from Manyame River. The cost of constructing Kunzvi Dam, expected to supply water to Harare and its surroundings, has increased almost seven-fold since last year owing to continued delays in starting the project. The cost now stands at $150 billion compared to $21 billion in March last year (2003) (http://www.dailytenders.co.za/General/News/Article/Article.asp?ID=666). The reason why this has been unsuccessful has been cited as being the lacks of funds to kick start the project. However, this project is a noble one as it provides a lot of solutions to the current water pollution crisis that has hit the upper Manyame catchment. The development of Kunzvi Dam would also mean that the capital city and its satellite towns would get fresh water, free from industrial effluent, instead of recycled water the city is currently using.

The dam is planned to be built upstream of the urban settlements and thus this takes care of the issue of the city being in the catchment of its own water supply. As a result there will be less pressure on Lake Chivero since water abstraction will be reduced, meaning there will be less concentration of pollutants in the water. If this “dream” finally turns into a reality, the problems faced by the Harare City council pertaining to water and water treatment will be greatly reduced.

Public participation

One of the four main principles at the core of Integrated Water Resources Management (IWRM) as enunciated in the Dublin Principles states that water development and management should be based on a participatory approach that involves users, planners and policy makers at all levels(SADC, 2001; Solanes *et al*., 1999; GWP, 1999). It has been clearly highlighted that the public has been isolated in the decision making process. The policy makers as well as the decision makers have completely isolated the public and taken upon themselves to control all the decisions and thus they have excluded the most important group of people in the process. The following are important points for public participation:

- In democratic societies, government policy agendas, in this case with respect to fresh water resources are fundamentally defined by the public.
- Policies and decisions that include significant inputs from public participation (consultation) are to some extent publicly "owned".
- Public participation enables government and water managers to "tap into" public knowledge.
- Everyone affected by decisions will not feel their views were not considered (even if they were not completely utilised).
- Following public participation, decisions can often be reached more quickly (there are likely to be fewer time consuming objections).
- It is good business sense to give the customer (i.e. the public) what it wants; and
- Best environmental practice management (BPEM) recognizes the good sense of proactive community consultation. (Source: UNEP 2000)

Public participation provides individuals and groups with the means to inform decision-makers about their views on given water issues. This is a crucial reason for public participation in all processes involved in the protection of freshwater bodies. Public participation also is a mechanism whereby people can express themselves and act with mutual responsibility to promote equity and sustainability, so as to achieve a desired goal.

There is an urgent need for sustained public awareness campaigns to impress on the residents of the Lake Chivero environs of the close linkage between their activities and the waters they drink. Many Harare or Chitungwiza residents are unaware of the fact that what they perceive as dirty street water eventually ends up on the meal table (Magadza 2003). The public also needs to know the intimacy between sewage outflow and the water quality of Lake Chivero and the cost of its treatment. Wastewater treatment plants and water abstraction plants have been traditionally out of bounds from the public. Whatever the reasons for this, it reinforces public ignorance of the state of the water resources while providing an excuse for the local authorities to be unaccountable to their ratepayers (Magadza 2003). IWRM has emphasised the need for the timely provision of information to decision makers for effective water management in a participatory manner (Haddad, 1996).

Penalising polluting industries

It has been highlighted that industries are the main culprits through their release of waste material that clearly overshoot the legal emission levels. Since the fines are so low that they do not inhibit such practices, it is only right and sensible to impose prohibitive fines that result in industries investing in water purifying machinery that will enable them to release effluent that conforms to the WHO levels. Failure which, the industries must be taken to court and either instructed to desist from polluting or risk closure. As much as we would need the industries for productivity purposes, they should realise that their activities are a major threat to the health of millions of people as well as the welfare of the ecosystem.

Wetlands as a purification tool

Marshes, swamps and bogs are collectively termed wetlands. They may also act as filters of sediments and organic matter. Wetland processes, both biological and chemical, such as nitrification and denitrification in the nitrogen cycle transforms the majority of the nitrogen entering wetlands causing between 70% and 90% to be removed (Reilly 1991, Gilliam 1994). In developed countries, one of the best methods of dealing with water pollution has been that of wetland use. This is a very feasible technical possibility to the Chivero problem. The Mukuvisi River has been seen to have a considerable self-purification capacity (Muchena 1997, Tendaupenyu 2002). It was observed that a wetland measuring an area of 20969.52m^2 and spanning a mere 1500m was able to improve water quality by approximately 50% (Tendaupenyu 2002). Constructing larger wetlands throughout the course of the rivers and building weirs to ensure a constant water velocity would thus improve the water quality substantially (Tendaupenyu 2002). This has been proven to be effective in the Cis Balaton situation in Central Europe where constructed wetlands saved a polluted Lake Balaton and led to its rehabilitation despite undergoing serious periods of pollution.

Many seasonal and permanent streams within the Lake Chivero catchment have attendant wetlands which used to be left as ecological lungs for the city. Magadza (2003) recommends that the authority re-examines its current policy of converting wetlands into residential or industrial areas, or condoning cultivations on such wetlands. It is further recommended that wetlands of streams associated with the residential areas should be managed for surface run-off, and where possible, wetlands should be constructed for this purpose. Such wetlands, when properly managed and landscaped, can serve both as recreational and nature conservation areas while performing valuable services in water quality management.

Sound governance

It cannot be disputed that governance that sets to protect its laws and encourages its citizens to abide by these laws creates a conducive environment for environmental protection and sustainable development. No amount of technological prowess can circumvent bad governance (Magadza 2003). There is thus a need for all involved to stick to the laid out emission levels. It is through this and the proper policing of such laws that will enable the Lake to be rehabilitated. The general principles for sound governance may include openness, participation, accountability, effectiveness and coherence (European Environmental Bureau 2001).

Need for continued monitoring

In the event that the situation is brought under control, there is a need for the responsible authorities to continually monitor the inputs into Lake Chivero from its catchment. In so doing, any breaches in pollution levels can be identified and dealt with well in time. This will save the authorities both time and money as the problem is controlled well before it proliferates.

Proper planning when expanding residential areas

The sewerage facilities in the Chivero catchment have failed to cater for the ever-increasing population of the settlements in this catchment. As a result, effluent from these facilities has breached the limits set by the W.H.O. The need for effective planning before developing an area cannot be over-emphasised. If there must be a new residential area, it must be located in areas that firstly do not "violate" the environment, that is, in areas such as wetlands that serve a purpose in water purification. The service facilities should be able to cater for the expansion in areas already established to make sure that there is a balance in the sewage entering the facility and the quality of the treated water. Planners should thus take into consideration the future projections of the population and plan basing on the estimates rather than on current figures because these are only temporary as a result of an influx of people in most residential areas. Implementing sound practices not only serves to protect the environment, but also ensures that money if saved and diverted to other projects that can benefit that particular area. It is essential that effluent discharged into a watercourse is of high quality and the degree of pollution is such that the self-purification capacity of the river is not overloaded (Mason 1996).

REFERENCES

Ballatore, T. J., Muhandiki, V. S. 2001. *The Case for a World Lake Vision International* Lake Environment Committee, Kusatsu, Shiga, Japan

Belausteguigoitia, J. C. 2004**.** Causal Chain Analysis and Root Causes: The GIWA Approach. *Ambio*, **33**: 7-12.

Bowyer-Bower, T. A. S., Mapaure, I., Drummond, R. B. 1996. Ecological degradation in cities: Impact of urban agriculture in Harare, Zimbabwe. *Journal of Applied Science in Southern Africa* **2**: 53-68

Bourke, A. T. C. and Hawes, R. B. 1983. Freshwater cyanobacteria (blue-green algae) and human health. *Medical Journal of Australia* **11**: 491-492.

Burke, N. A. and Thorton, J. A. 1982. The creation of Lake McIlwaine: history and design. In: Thornton, J. A. and Nduku, W. K. (eds.) Lake McIlwaine. *The Eutrophication and Recovery of a Tropical Man-made Lake*. Dr. W. Junk Publishers, The Hague, The Netherlands.

Carin van Ginkel 2002**.** Trophic status assessment Executive summary. Institute for Water Quality Studies Department of Water Affairs and Forestry. http://www.dwaf.gov.za/iwqs/eutrophication/NEMP/default.html

Carmichael, W. W. 1994. The toxins of cyanobacteria. *Scientific American* **270:** 64-72.

Desanker, P. Magadza, C. H.D. 2001. In: *Climate Change 2001: Impacts, Adaptations and Vulnerability* (eds J. J. McCarthy, O. F. Canziani, N. A. Leary, D. J. Dokken & K. S. White) pp. 487-531. Cambridge University Press, Cambridge.

European Environmental Bureau 2001. Good Governance for Environment Annual Conference of the European Environmental Bureau Brussels, 27-28 September 2001. pp1-20

Falconer, I. R., Burch, M., Steffenson, D. A., Choice, M. and Coverdale, D. R. 1994 Toxicity of the blue-green algae (cyanobacterium) *Microcystis aeruginosa* in the drinking water to growing pigs, as an animal model for human injury and risk assessment. *Environmental Toxicology and Water Quality* **9**: 131-139.

Gilliam, J.W. 1994. Riparian Wetlands and Water Quality. *Journal of Environmental Quality* **23**: 896-900.

Government of Zimbabwe, 2000 *Statutory Instrument (S.I.) 274 of 2000, Water (Waste and Effluent Disposal) Regulations*, Government Publications, Harare.

Greenline 1997. Harare City Council under pressure to end water pollution problems. **1.11**: 22-23.

Greichus, Y.A, A., Amman, B. D., Hopcraft, J. 1978. Insecticides, Polychlorinated Biphenyls and Metals in African Lake Ecosystems III. Lake Nakuru, Kenya. *Bulletin of Environmental Contamination and Toxicology*. **19**:454-461.

Gumbo, B. 1997. *Water and Sanitation for all: Partnerships and Innovations. Integrated Water Quality Management in Harare*. WEDC Conference, Durban, South Africa. pp1-5.

GWP, 1999. *IWRM at a glance*. Global Water Partnership, Stockholm

Haddad B.M. 1996. *Evaluating the market niche: Why long term rural to urban inter-regional markets for water have not formed in California*. University of California. Energy and Resources PhD thesis. USA

http://qsilver.queensu.ca/~mspadmin/pages/In_The_News/2003/December/72.htm
http://www.epa.gov/maia/html/eutroph.html
http://www.herald.co.zw/index.php?id=27797&pubdate=2003-12-30
http://www.pref.ibaraki.jp/prog/lake/lake11.htm
http://www.unep.or.jp/ietc/Publications/TechPublications/TechPub-12/intro.asp

Irvine, K.N., K.M. Frothingham, M.C. Rossi, S. Pickard, J. Atkinson, and T. Bajak. 2003**.** Contaminated sediment in the Buffalo River area of concern-historical trends and current conditions. Sediment Quality Assessment and Management: Insight and Progress, M. Munwar (ed.), Ecovision World Monograph Series*, Aquatic Ecosystem Health and Management Society*, pp. 81-112.

JICA Report 1996. *The study on Water Pollution Control in the Upper Manyame River Basin in The Republic of Zimbabwe*. MLGRUD, Nippon Jogesuido Sekkei Co. Ltd. Nippon Koei Co. Ltd, July.

Johansson, S. and Olsson, M. 1998**.** *Investigations of toxic algal blooms in drinking water reservoir of Harare, Zimbabwe*. University of Lund.

Kairu, J. K. 2001. Wetland use and impact on Lake Victoria, Kenya region. *Lakes & Reservoirs:ResearchandManagement*.**6** (2):117

Lawton, L. A., Edwards, C. and Codd, G. A. 1994. Extraction and High performance Liquid Chromatographic method for the determination of Microcystins in raw and treated waters. *Analyst* **119**: 525-1530.

Lepisto, L., Lahti, K., Fardig, M., Neimi, J. 1992**.** Removal efficiency of algae and especially cyanobacteria in different waterworks. *National Board of Waters and environment, Finland Report.*

Magadza, C. H. D. 2003. Lake Chivero: A Management case study. *Lakes & Reservoirs: Research and Management*. **8**: 69-81.

Magadza C. H. D. 2002. *Emerging issues in sustainable water resources management in Africa*. In: *Lakes and Reservoirs as International Water Systems: Towards a World Vision* (eds L. Jansky & J. I. Uitto) pp. 14-27. United Nations University, Tokyo.

Magadza, C. H. D. 1997. *Water pollution and catchment management in Lake Chivero*. In: *Lake Chivero, a Polluted Lake* (Ed. N. A. G. Moyo) pp. 13-26. International Union for the Conservation of Nature and Natural Resources. University of Zimbabwe Publications, Harare

Magadza C. H. D. 1994. An evaluation of eutrophication control in Lake Chivero using multivariate analysis of plankton samples. In: Studies in the Ecology of Tropical Zooplankton (Eds H. Dumont, J. Green & H. Masundire) pp. 277-92. Kluwer Academic Press, London.

Magadza, C.H.D. 1984. An analysis of siltation rates in Zimbabwe. *Zimbabwe Science News* **18**: 63-64.

Magadza, C. H. D. 1984. *Special Problems in lakes/reservoir Management in Tropical Southern Africa*. The 6th International Conference on the Conservation and Management of Lakes. Kasumigaura.

Mandaville, S. M. 2000**.** Lake Data of Relatively Undisturbed Lakes within Nova Scotia; Provincial Averages; CCME, Health & Welfare Canada, and OME Guidelines.

Marshall, B. E. 1996. L*ake Chivero after Forty Years: the Impact of Eutrophication.* In:

Moyo, N. A. G. 1996 *Lake Chivero A Polluted Lake*. International Union for the Conservation of Nature and Natural Resources. University of Zimbabwe Publications, Harare

Marshall, B. E. 1994. *Ecology and Management of the Manyame lakes*. In: T. Matiza and S.A. Crafter (eds.), *Wetlands Ecology and priorities for conservation in Zimbabwe: Proceedings of a seminar on wetlands ecology and priorities for conservation in Zimbabwe,* Harare, pp. 55-67. IUCN Gland, Switzerland.

Marshall, B. E. 1991. Toxic cyanobacteria in Lake Chivero: A possible health hazard. *Transactions of Zimbabwe Scientific Association* **65**: 16-19.

Marshall B. E. & Falconer A. C. 1973. Physiochemical aspects of Lake McIlwaine (Rhodesia), a eutrophic tropical impoundment. *Hydrobiologia* **42**, 45-62.

Mason, C. F. 1996. *Biology of freshwater pollution*. Longman, London.

Mathutu, A. S., Mwanga, K., Simoro, A. 1996. *Impact Assessment of Industrial and Sewage effluents on Water quality of the Receiving Marimba River in Harare*. In: Moyo, N.A.G. 1996 *Lake Chivero A Polluted Lake*. University of Zimbabwe Publications.

Mathutu, A. S., Zaranyika, M. F., Tafirenyika, S. Chibanda, B. 1995. Impact assessment of sewage effluent discharges on the quality of the receiving lower Mukuvisi River waters in Harare, Zimbabwe. *Journal of Environmental Science and Health*. **A30**: 281-297.

Mhlanga, A. T. & Madziva, T. J. 1990. Pesticide residues in Lake McIlwaine, Zimbabwe. *Ambio,* **19**: 368-372.

Moyo, N. A. G. 1996. *Lake Chivero A Polluted Lake*. University of Zimbabwe Publications, Harare

Munzwa, K. 1982. *Land use survey of the Upper Hunyani Catchment. Monographiae Biologicae* **49:**11.

Ndebele, R. M. 2003. Some aspects of the ecology of phytoplankton in Lake Chivero, Harare, Zimbabwe. M.Sc. thesis. University of Zimbabwe

Nduku W. K. 1976**.** The distribution of phosphorus, nitrogen and organic carbon in the sediments of Lake McLain, Rhodesia. *Transactions of the* ***Rhodesian Scientific Association*** **57**, 45-60.

Nhapi, I. 2004. *Options for Wastewater Management in Harare, Zimbabwe. A. A*. Balkema Publishers, London, UK.

Nhapi, I. and Hoko, Z. *A.* 2002**.** *Cleaner Production Approach to Urban Water Management: Potential for Application in Harare, Zimbabwe* 3rd WaterNet/Warfsa Symposium Water Demand Management for Sustainable Development', Dar es Salaam, 30-31 October 2002

Nhapi, I., Hoko, Z., Siebel, M. A., Gijzen, H. J. 2001. *Assessment of the major water and nutrient flows in the Chivero catchment area, Zimbabwe*. 2nd WARFSA/WaterNet Symposium: Integrated Water Resources Management: Theory, Practice, Cases; Cape Town, 30 – 31 October 2001.

OME (Ontario Ministry of Environment) 1991. Water management, Provincial Water Quality Objectives and Guidelines.

Reilly, W. 1991**.** US *Environmental Protection Agency*. Testimony for July 10, 1991. Hearing before the Senate Subcommittee on Environmental Protection regarding Section 404 of the Clean Water Act.

SADC. 2001. *Strategies for the promotion of integrated water resources management*. SADC Water Sector Coordination Unit, Maseru.

Siebel, M. A. and Gijen, H. J. 2002. *Application of Cleaner Production Concepts in Urban Water Management, paper presented at the Environmental Technology and Management Seminar 2002*, Bandug, Indonesia, January 9-10, 2002

Solanes M. and Gonzalez-Villarreal F. 1999. *The Dublin Principles of Water as Reflected in a Comparative Assessment of Institutional and Legal Arrangements f for integrated Water Resources Management*. Global Water Partnership/Swedish International, Stockholm.

Standards Association of Central Africa 1972**.** Standards of waste or effluent water. *CAS No. Z21:1-10*

Tendaupenyu, I. H. 2002. Role of wetlands in the self-purification of streams using the Mukuvisi River (Harare, Zimbabwe) as a case study. Undergraduate project. Harare, Zimbabwe.

Thorton, J. A, Nduku, W. K. (eds) 1982. *Lake McIlwaine: the Eutrophication and recovery of a Tropical Lake.* Dr. W. Junk, The Hague.

Thorton, J. A. 1980. A comparison of the summer phosphorous loading to three Zimbabwean water supply reservoirs of varying eutrophic states. *Water SA* **6**, 163-170.

UNEP 2003. World Lake Vision: A Call to Action. World Lake Vision Committee.

UNEP 2002. United Nations Environmental Programme. National Parks in Zimbabwe (www.unep.net)

UNEP 2000**.** *How to involve the public in protecting them from degradation*. Lakes and Reservoirs. Volume 4.

Wigley, T. M. L., Raper, S. C. B., Hulme, M. Salmon, M. 2000**.** Model for the Assessment of Greenhouse-gas Induced Climate Change. The Climatic Research Unit. UNDP/NCSP.

Vollenweider, R. A. 1975**.** Input-output models with special reference to the phosphorus loading concept in limnology. *Schweitz Z. Hydrol.*, **37,** 53-84.

World Bank, 1998. *African Development Indicator*s, WB, Washington.

World Health Organization 1998. *Guidelines for drinking water quality*, 2nd ed. (Addendum to Vol. 1.) Recommendations. Geneva. Pp 13-14.

Zaranyika, M. F. 1996. Sources of Levels of pollution along Mukuvisi River: A Review. In: Moyo, N. A. G. 1996 *Lake Chivero A Polluted Lake*. University of Zimbabwe Publications

Zilberg, B. 1966. Gastro-enteritis in Salisbury European Children. *Central African Journal of Medicine*, **12**: 164-166.

Zimbabwe National Health Profile (ZNHP). 1990-2000**.** Ministry of health and Child welfare, Epidemiology and Disease Control, National Health information and surveillance unit, Harare, Zimbabwe

APPENDICES

Appendix 1: Trophic status of some South Africa Reservoirs (Magadza 2004, Carin van Ginkel 2002).

	Total phosphorous		
Trophic state	Lower range (mg/l)	Upper range (mg/l)	No. of dams
Hypereutrophic	0.145	0.545	9
Eutrophic	0.084	0.221	11
Mesotrophic	0.034	0.115	10
Oligotrophic	0.012	0.047	10

Appendix 2: Two-layer model parameters used in simulation of current state of Lake Chivero

		Epilimnion	Hypolimnion
Nitrogen	mgN/l	1.97	2.1
Phosphorous	mgP/l	0.635	0.67
Diatom	mgChla/l	5.42	4.065
Blue-green algae	mgChla/l	6.6	0
Other phytoplankton	mgChla/l	7.8	0
Zooplankton	mgDW/l	2.28	2.24
Detritus	mgDW/l	125.4	164.16
Dissolved organics	mgCOD/l	33.84	37.43
Dissolved oxygen	mgO_2/l	6	0.15
*Nitrogen in Sediment	mgN/l	0	48.89
*Phosphorous in sediment	mgP/l	0	10.2
*Dissolved organics in sediments	mgC/l	0	366.96

*Values in per litre of sediment

Appendix 3: Initial data composer values in two layer model

Water temperature	T	^{o}C	18
Intensity of sunlight	I	$MJ/(m^2*D)$	13
Wind speed	W	m/s	3
Inflow rate	Q	m^3/d	680800
Outflow rate	Qout	m^3/d	591200
Nitrogen in influent	N	mg/l	7.9
Phosphorous in influent	P	mg/l	2.37
Diatom in influent	M1	mgChla/l	3
Blue green algae in influent	M2	mgChla/l	3
Other phytoplankton in influent	M3	mgChla/l	3
Zooplankton in influent	Z	mgDW/l	2
Detritus in influent	D	mgDW/l	3
Dissolved organics in influent	C	mgCOD/l	3
Dissolved oxygen in influent	DO	mgO_2/l	4

Appendix 4: Initial data input for 1-layer model lake morphology for Lake Chivero (Lake morphology constants).

Lake Depth (Z)	9.5meters
Water residence time	1.6 years
Sedimentation rate	10meters/year
a (constant)	1

Appendix 5: Initial data input for 1-layer model for Lake average nitrogen and phosphorous levels

Phosphorous		Nitrogen	
*P water	0.6mg/l	*N water	2mg/l
P sediment	$12g/m^2$	N sediment	$100g/m^2$
*P loading	$24.4g/m^2/yr$	*N loading	$108.9g/m^2/yr$
P release	0.01/yr	N release	0.01/yr
P bound	0.05	N bound	0.1
		Denitrification	0.05

*Source Nhapi (2001)

Appendix 6: Lake Chivero Morphology

	Epilimnion	Hypolimnion
Mean water depth, m	6	3.5
Surface area, m^2	26449000	180000000
Circulation flow, m^3/(d*unit)	1055053	1055053
Mixing rate (T<=20°C)	7	0
Mixing rate (T>20°C)	0	0
Sediment depth, m	----	0.15